

RowHammer, RowPress & Beyond

Can We Be Free of Bitflips (Soon)?

Onur Mutlu

omutlu@gmail.com

<https://people.inf.ethz.ch/omutlu>

28 February 2024

UC Berkeley

SAFARI

ETH zürich

Carnegie Mellon

How Reliable/Secure/Safe is This Bridge?



Collapse of the “Galloping Gertie”



How Safe & Secure Are These People?



Security is about preventing unforeseen consequences

How Safe & Secure Are Our Platforms?



Security is about preventing unforeseen consequences

What Is RowHammer?

- One can **predictably induce bit flips** in commodity DRAM chips
 - >80% of the tested DRAM chips are vulnerable
- First example of how a **simple hardware failure mechanism** can create a **widespread system security vulnerability**

WIRED

Forget Software—Now Hackers Are Exploiting Physics

| | | | | |
|----------|---------|--------|------|---------|
| BUSINESS | CULTURE | DESIGN | GEAR | SCIENCE |
|----------|---------|--------|------|---------|

ANDY GREENBERG SECURITY 08.31.16 7:00 AM

SHARE



SHARE
18276



TWEET

FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

An “Early” Position Paper [IMW’13]

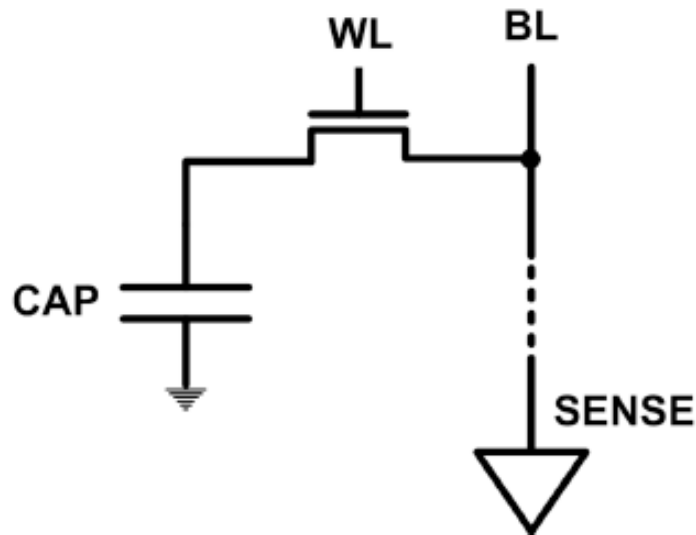
- Onur Mutlu,
"Memory Scaling: A Systems Architecture Perspective"
*Proceedings of the 5th International Memory Workshop (**IMW**), Monterey, CA, May 2013. Slides
(pptx) (pdf)
EETimes Reprint*

Memory Scaling: A Systems Architecture Perspective

Onur Mutlu
Carnegie Mellon University
onur@cmu.edu
<http://users.ece.cmu.edu/~omutlu/>

The DRAM Scaling Problem

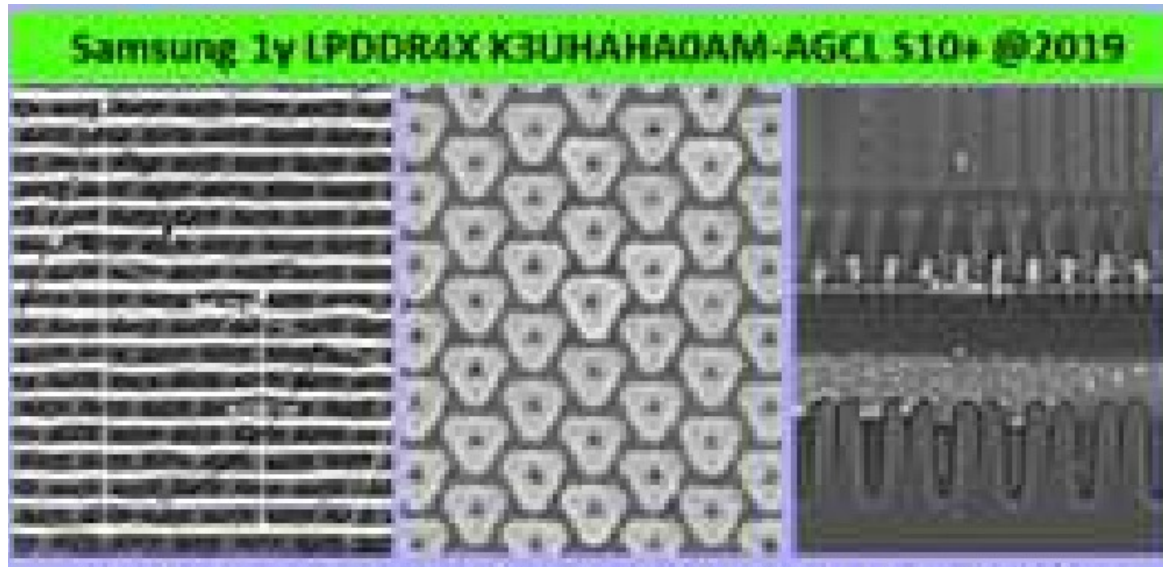
- DRAM stores charge in a capacitor (charge-based memory)
 - Capacitor must be large enough for reliable sensing
 - Access transistor should be large enough for low leakage and high retention time
 - Scaling beyond 40-35nm (2013) is challenging [ITRS, 2009]



- DRAM capacity, cost, and energy/power hard to scale

The DRAM Scaling Problem

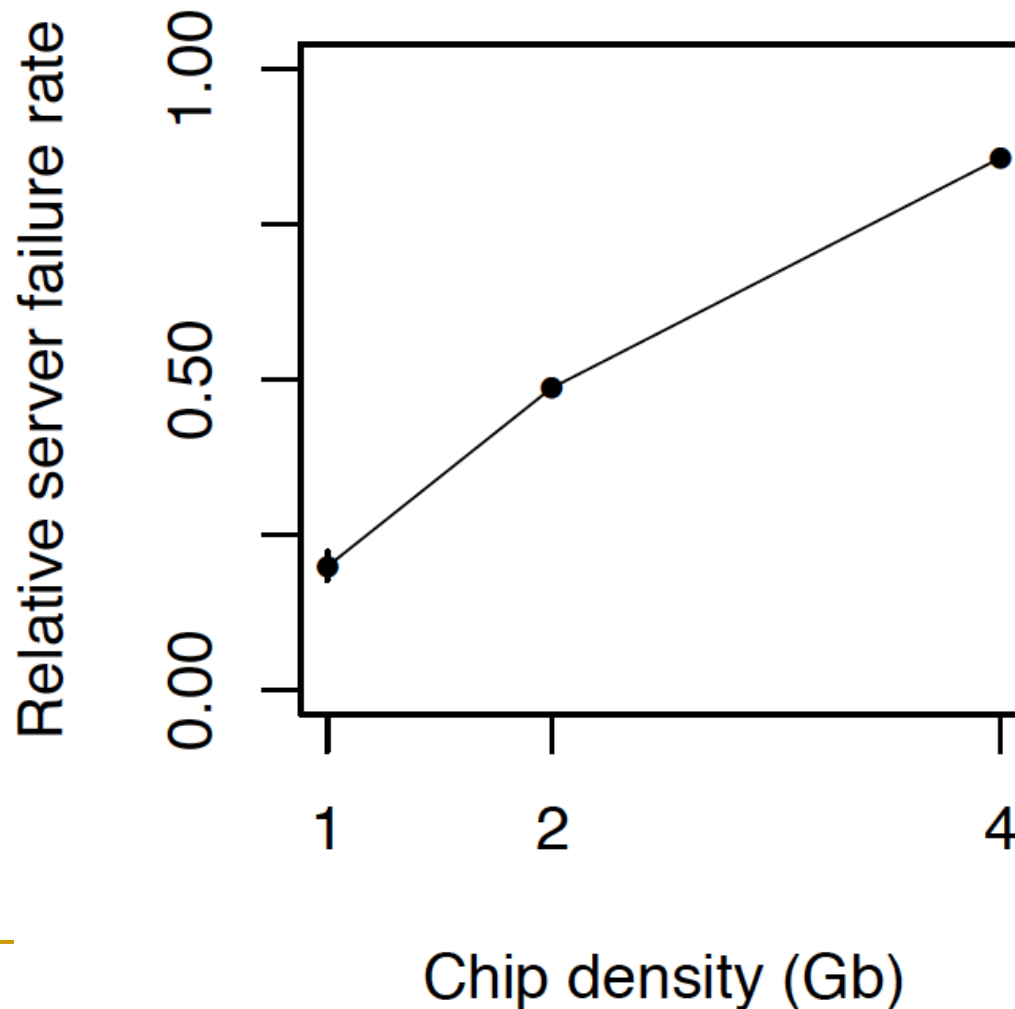
- DRAM stores charge in a capacitor (charge-based memory)
 - Capacitor must be large enough for reliable sensing
 - Access transistor should be large enough for low leakage and high retention time
 - Scaling beyond 40-35nm (2013) is challenging [ITRS, 2009]



- DRAM capacity, cost, and energy/power hard to scale

As Memory Scales, It Becomes Unreliable

- Data from all of Facebook's servers worldwide
- Meza+, "Revisiting Memory Errors in Large-Scale Production Data Centers," DSN'15.



*Intuition:
quadratic
increase
in
capacity*

Large-Scale Failure Analysis of DRAM Chips

- Analysis and modeling of memory errors found in all of Facebook's server fleet
- Justin Meza, Qiang Wu, Sanjeev Kumar, and Onur Mutlu,
"Revisiting Memory Errors in Large-Scale Production Data Centers: Analysis and Modeling of New Trends from the Field"
Proceedings of the 45th Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Rio de Janeiro, Brazil, June 2015.
[[Slides \(pptx\)](#)] [[pdf](#)] [[DRAM Error Model](#)]

Revisiting Memory Errors in Large-Scale Production Data Centers: Analysis and Modeling of New Trends from the Field

Justin Meza Qiang Wu* Sanjeev Kumar* Onur Mutlu
Carnegie Mellon University * Facebook, Inc.

Infrastructures to Understand Such Issues



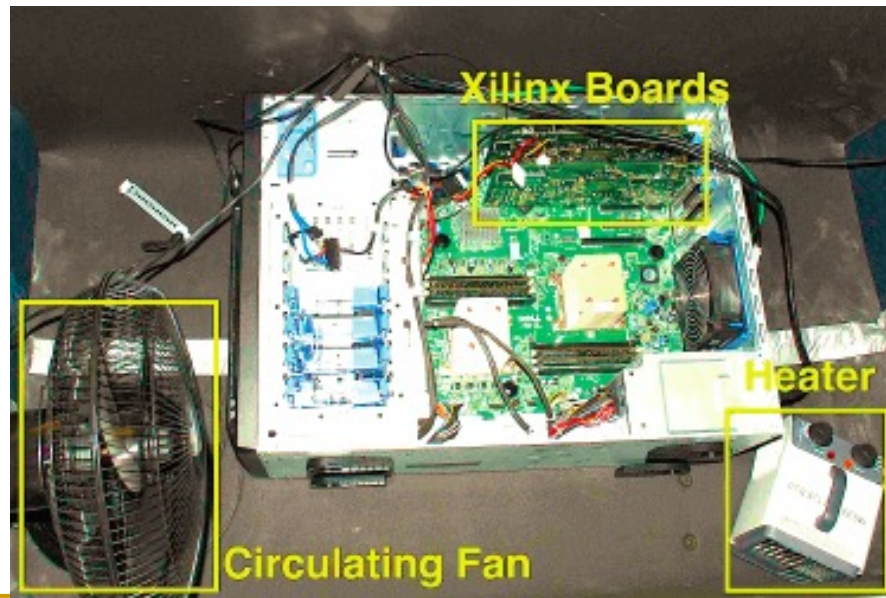
Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors (Kim et al., ISCA 2014)

Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common-Case (Lee et al., HPCA 2015)

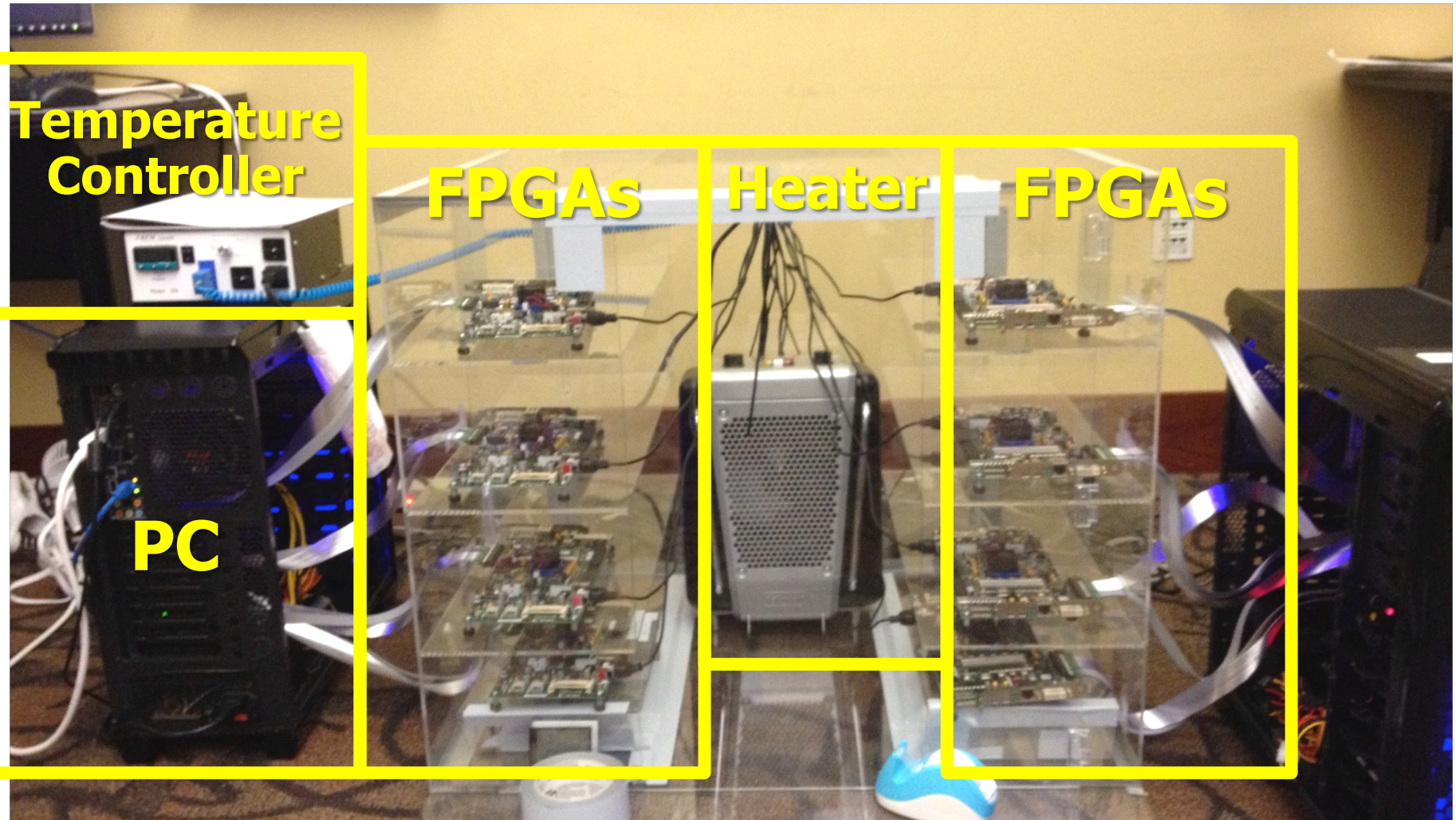
AVATAR: A Variable-Retention-Time (VRT) Aware Refresh for DRAM Systems (Qureshi et al., DSN 2015)

An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms (Liu et al., ISCA 2013)

The Efficacy of Error Mitigation Techniques for DRAM Retention Failures: A Comparative Experimental Study (Khan et al., SIGMETRICS 2014)



Infrastructures to Understand Such Issues



SoftMC: Open Source DRAM Infrastructure

- Hasan Hassan et al., “[SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies](#),” HPCA 2017.
- Flexible
- Easy to Use (C++ API)
- Open-source
[*github.com/CMU-SAFARI/SoftMC*](https://github.com/CMU-SAFARI/SoftMC)



SoftMC: Open Source DRAM Infrastructure

- Hasan Hassan, Nandita Vijaykumar, Samira Khan, Saugata Ghose, Kevin Chang, Gennady Pekhimenko, Donghyuk Lee, Oguz Ergin, and Onur Mutlu,

"SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies"

Proceedings of the 23rd International Symposium on High-Performance Computer Architecture (HPCA), Austin, TX, USA, February 2017.

[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)]

[Full Talk Lecture (39 minutes)]

[Source Code]

SoftMC: A Flexible and Practical Open-Source Infrastructure for Enabling Experimental DRAM Studies

Hasan Hassan^{1,2,3} Nandita Vijaykumar³ Samira Khan^{4,3} Saugata Ghose³ Kevin Chang³
Gennady Pekhimenko^{5,3} Donghyuk Lee^{6,3} Oguz Ergin² Onur Mutlu^{1,3}

¹ETH Zürich ²TOBB University of Economics & Technology ³Carnegie Mellon University
⁴University of Virginia ⁵Microsoft Research ⁶NVIDIA Research

DRAM Bender

- Ataberk Olgun, Hasan Hassan, A Giray Yağlıkçı, Yahya Can Tuğrul, Lois Orosa, Haocong Luo, Minesh Patel, Oğuz Ergin, and Onur Mutlu,
"DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips"
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD), 2023.
[[Extended arXiv version](#)]
[[DRAM Bender Source Code](#)]
[[DRAM Bender Tutorial Video](#) (43 minutes)]

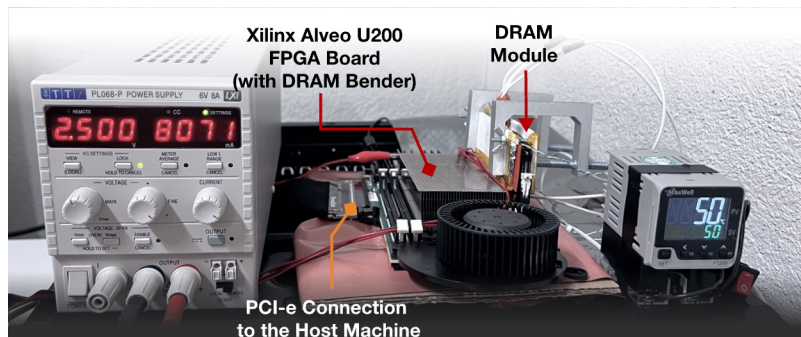
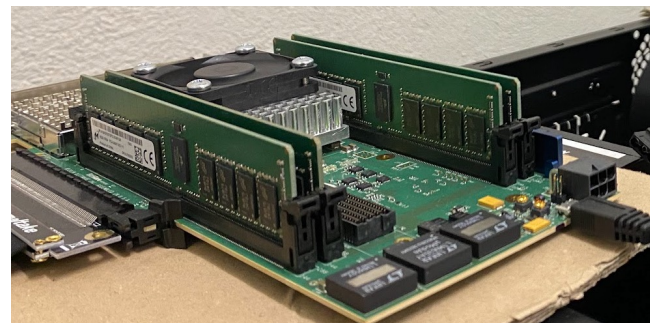
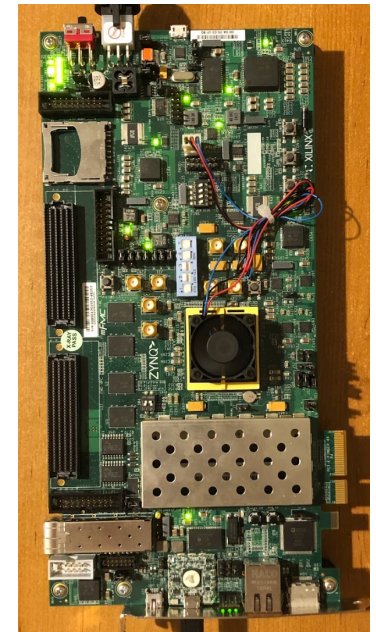
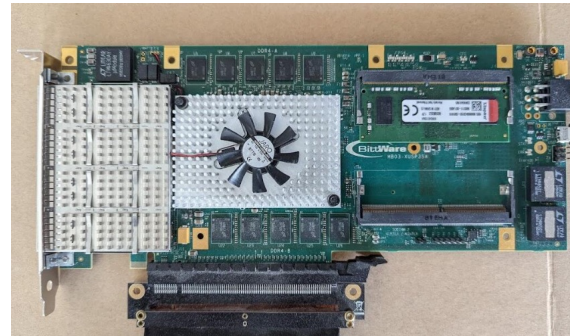
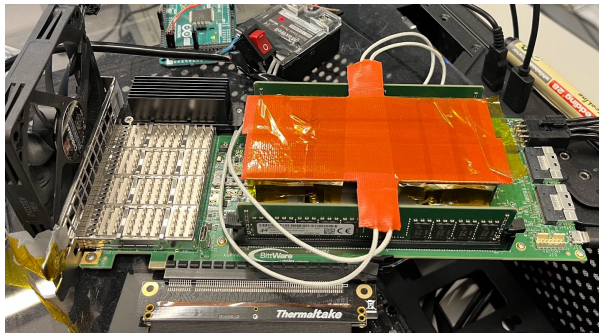
DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips

Ataberk Olgun[§] Hasan Hassan[§] A. Giray Yağlıkçı[§] Yahya Can Tuğrul^{§†}
Lois Orosa^{§⊙} Haocong Luo[§] Minesh Patel[§] Oğuz Ergin[†] Onur Mutlu[§]
 [§]*ETH Zürich* [†]*TOBB ETÜ* [⊙]*Galician Supercomputing Center*

DRAM Bender: Prototypes

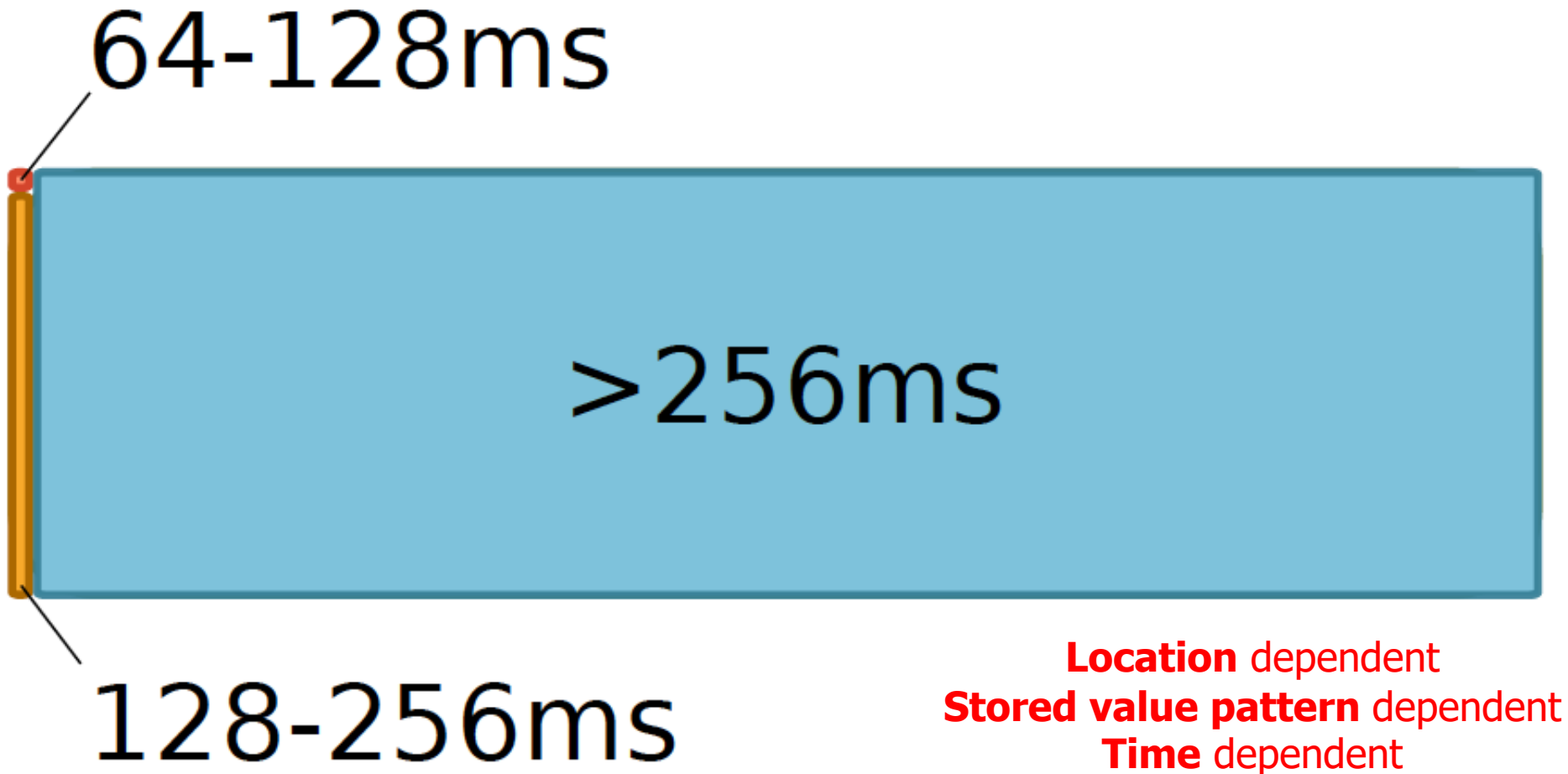
| Testing Infrastructure | Protocol Support | FPGA Support |
|-----------------------------------|------------------|------------------------|
| SoftMC [134] | DDR3 | One Prototype |
| LiteX RowHammer Tester (LRT) [17] | DDR3/4, LPDDR4 | Two Prototypes |
| DRAM Bender (this work) | DDR3/DDR4 | Five Prototypes |

Five out of the box FPGA-based prototypes



Data Retention in Memory [Liu et al., ISCA 2013]

- Retention Time Profile of DRAM looks like this:



RAIDR: Heterogeneous Refresh [ISCA'12]

- Jamie Liu, Ben Jaiyen, Richard Veras, and Onur Mutlu,
"RAIDR: Retention-Aware Intelligent DRAM Refresh"
Proceedings of the 39th International Symposium on Computer Architecture (ISCA), Portland, OR, June 2012. Slides (pdf)
[Invited Retrospective at 50 Years of ISCA, 2023 (pdf)]
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 (Retrospective (pdf) Full Issue).

RAIDR: Retention-Aware Intelligent DRAM Refresh

Jamie Liu Ben Jaiyen Richard Veras Onur Mutlu
Carnegie Mellon University

Analysis of Data Retention Failures [ISCA'13]

- Jamie Liu, Ben Jaiyen, Yoongu Kim, Chris Wilkerson, and Onur Mutlu,
**"An Experimental Study of Data Retention Behavior in Modern DRAM Devices:
Implications for Retention Time Profiling Mechanisms"**
Proceedings of the 40th International Symposium on Computer Architecture (ISCA), Tel-Aviv, Israel, June 2013. [Slides \(ppt\)](#) [Slides \(pdf\)](#)
[Invited Retrospective at 50 Years of ISCA, 2023 (pdf)]
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 (Retrospective (pdf) Full Issue).

An Experimental Study of Data Retention Behavior in Modern DRAM Devices: Implications for Retention Time Profiling Mechanisms

Jamie Liu^{*}
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213
jamiel@alumni.cmu.edu

Ben Jaiyen^{*}
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213
bjaiyen@alumni.cmu.edu

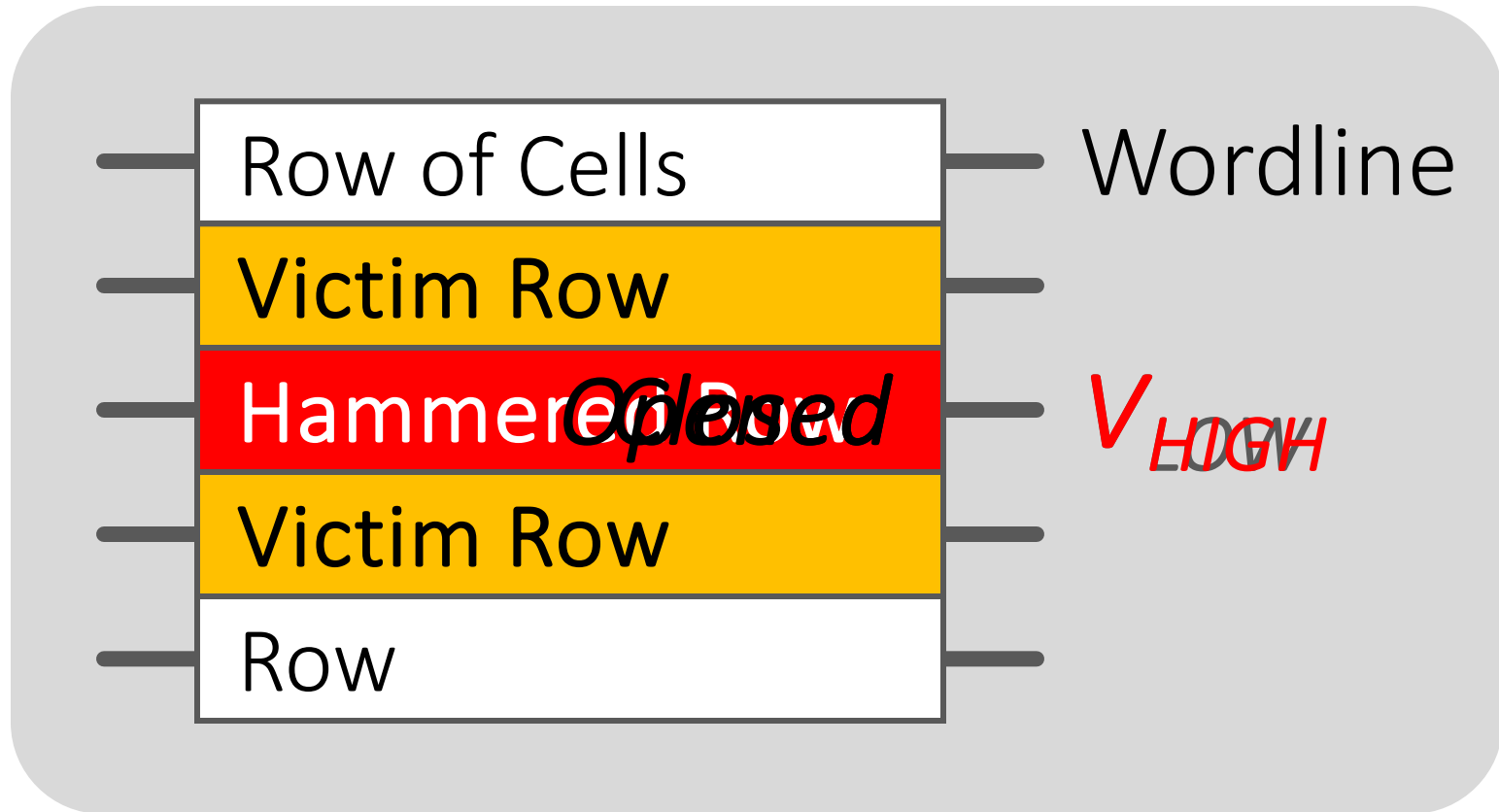
Yoongu Kim
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213
yoonguk@ece.cmu.edu

Chris Wilkerson
Intel Corporation
2200 Mission College Blvd.
Santa Clara, CA 95054
chris.wilkerson@intel.com

Onur Mutlu
Carnegie Mellon University
5000 Forbes Ave.
Pittsburgh, PA 15213
onur@cmu.edu

A Curious Phenomenon

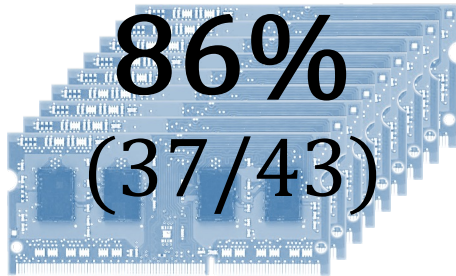
Modern DRAM is Prone to Disturbance Errors



Repeatedly reading a row enough times (before memory gets refreshed) induces **disturbance errors** in adjacent rows in **most real DRAM chips you can buy today**

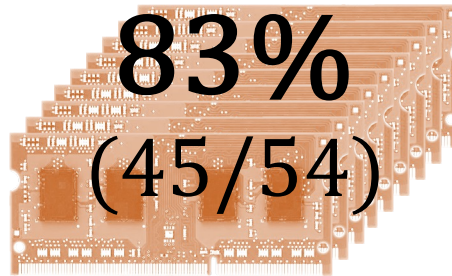
Most DRAM Modules Are Vulnerable

A company



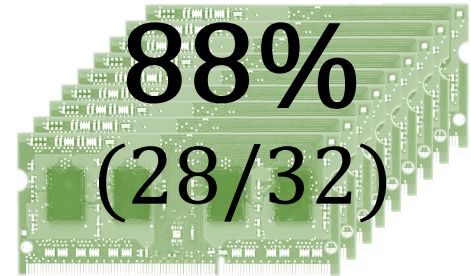
Up to
 1.0×10^7
errors

B company



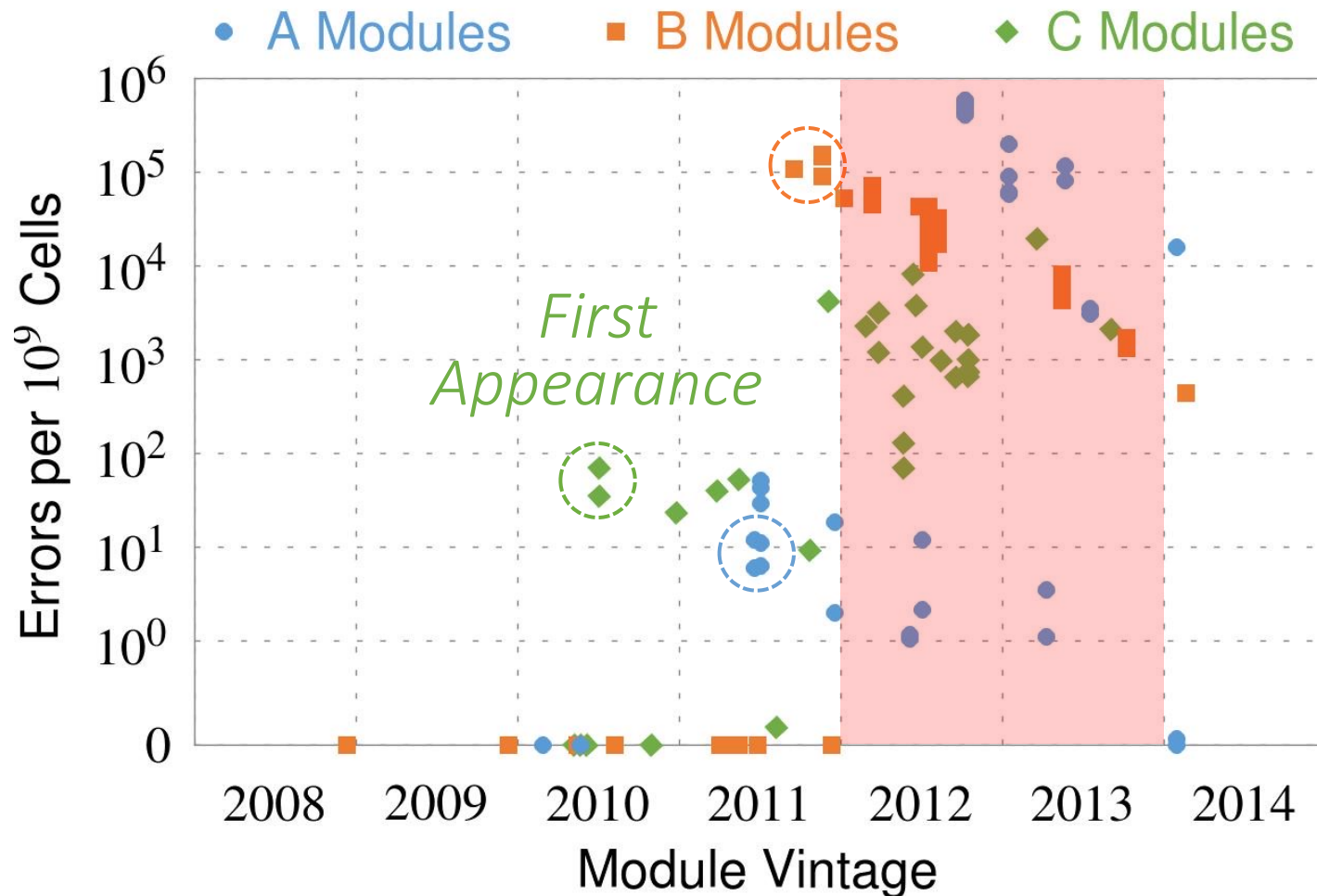
Up to
 2.7×10^6
errors

C company



Up to
 3.3×10^5
errors

Recent DRAM Is More Vulnerable



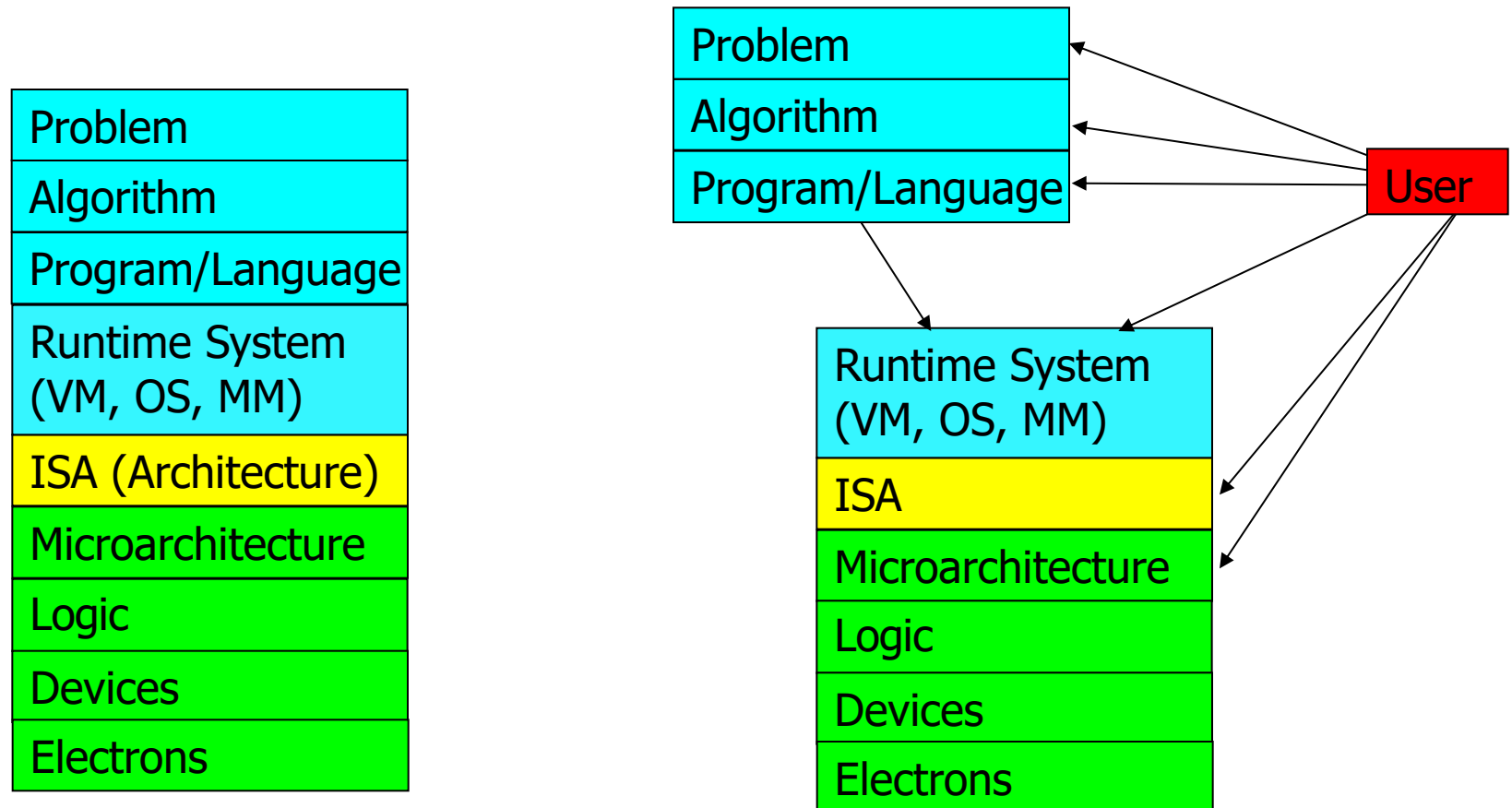
All modules from 2012-2013 are vulnerable

Why Is This Happening?

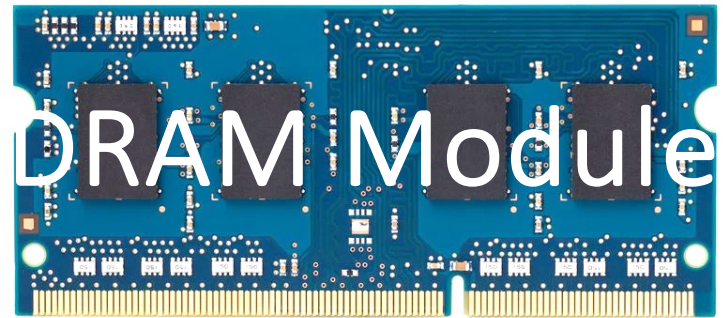
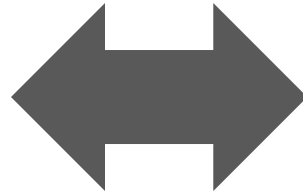
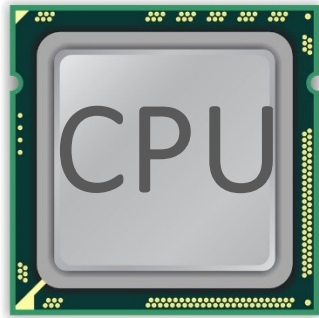
- DRAM cells are too close to each other!
 - They are not electrically isolated from each other
- Access to one cell affects the value in nearby cells
 - due to **electrical interference** between
 - the cells
 - wires used for accessing the cells
 - Also called cell-to-cell coupling/interference
- Example: When we activate (apply high voltage) to a row, an adjacent row gets slightly activated as well
 - Vulnerable cells in that slightly-activated row lose a little bit of charge
 - If RowHammer happens enough times, charge in such cells gets drained

Higher-Level Implications

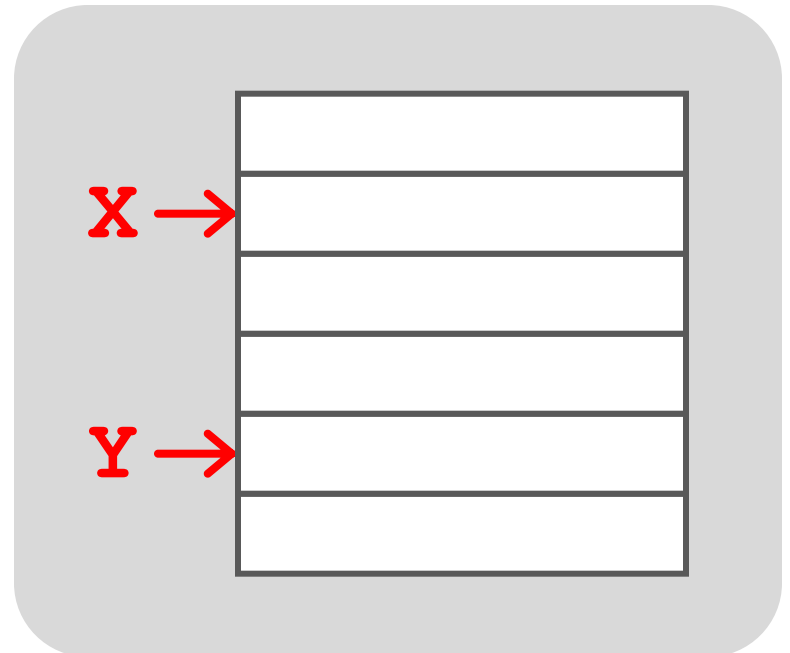
- This simple circuit level failure mechanism has enormous implications on upper layers of the transformation hierarchy



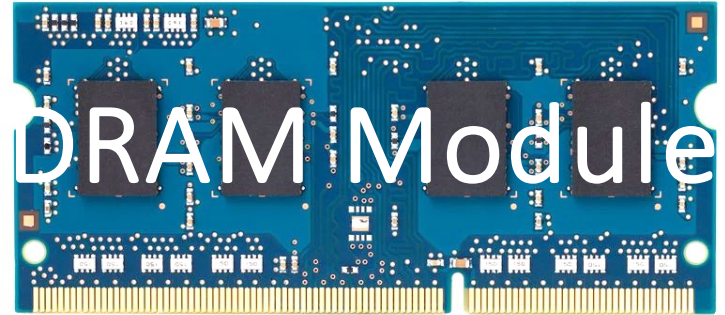
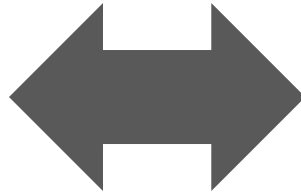
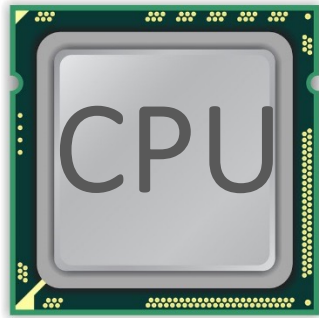
A Simple Program Can Induce Many Errors



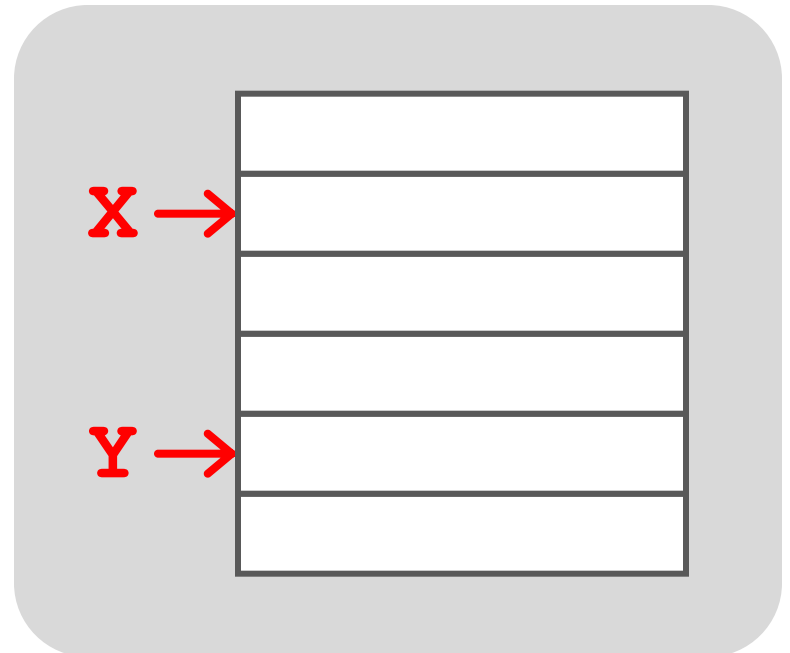
```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



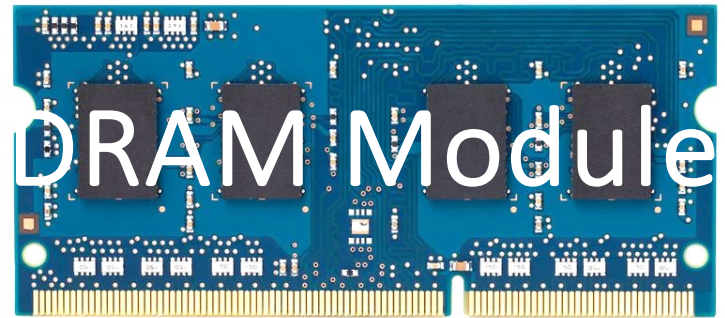
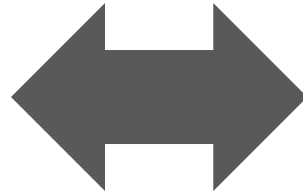
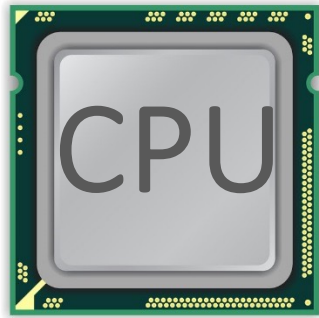
A Simple Program Can Induce Many Errors



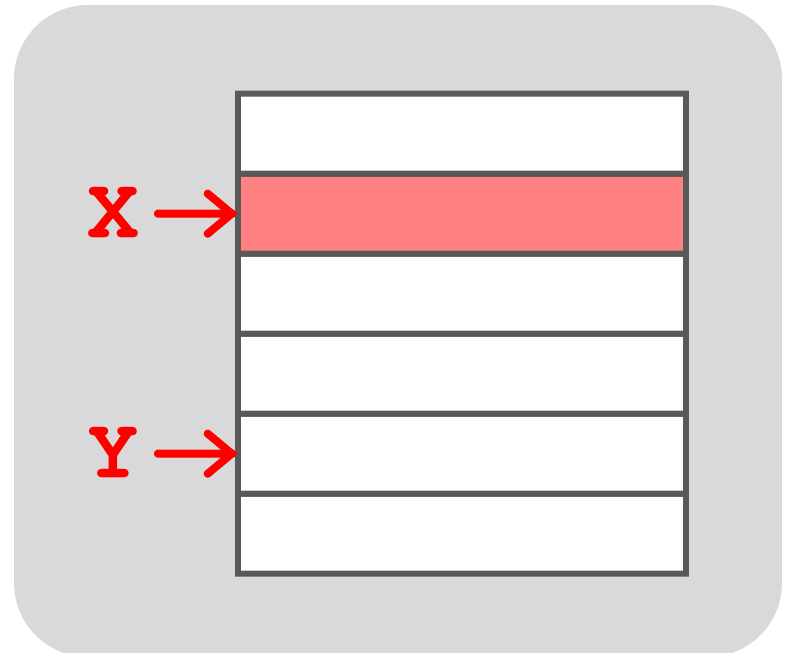
1. Avoid *cache hits*
 - Flush **X** from cache
2. Avoid *row hits* to **X**
 - Read **Y** in another row



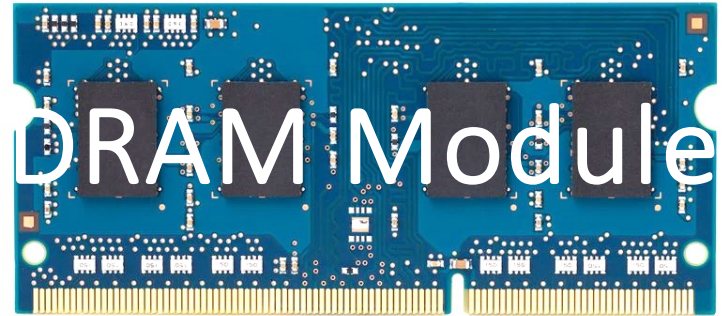
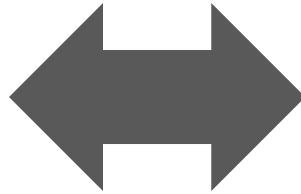
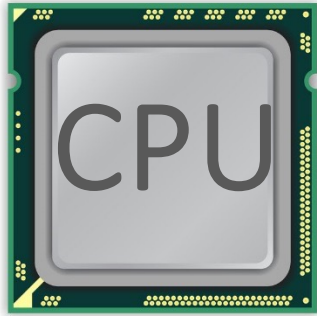
A Simple Program Can Induce Many Errors



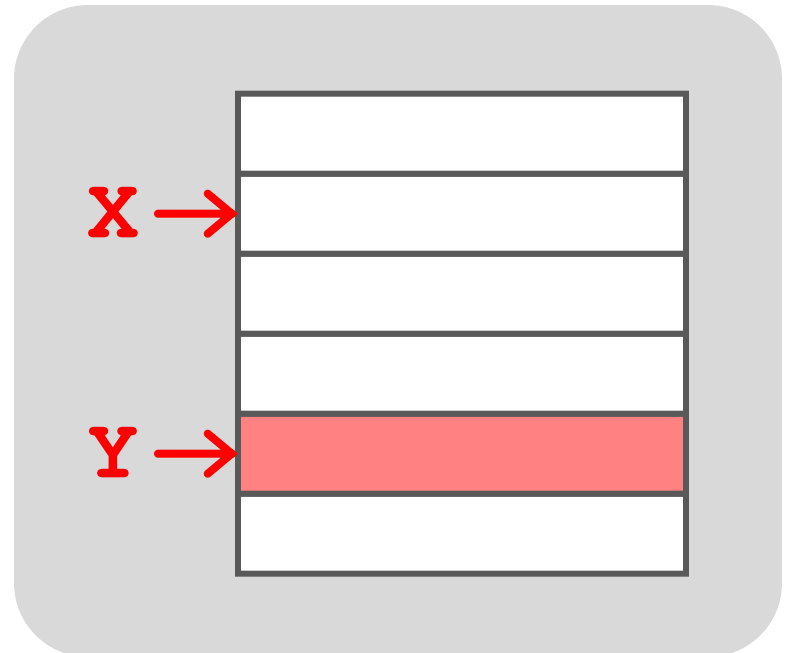
```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



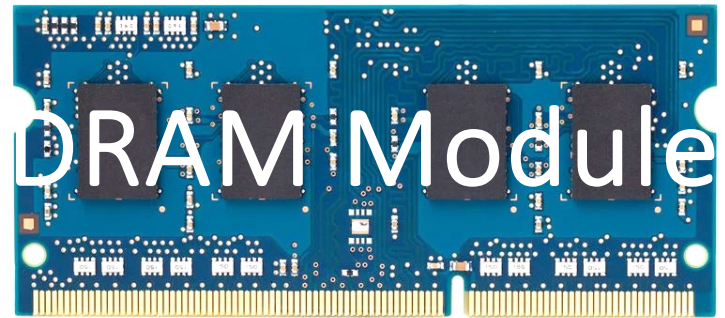
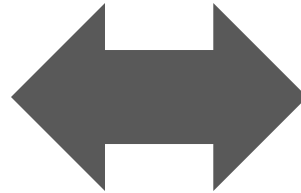
A Simple Program Can Induce Many Errors



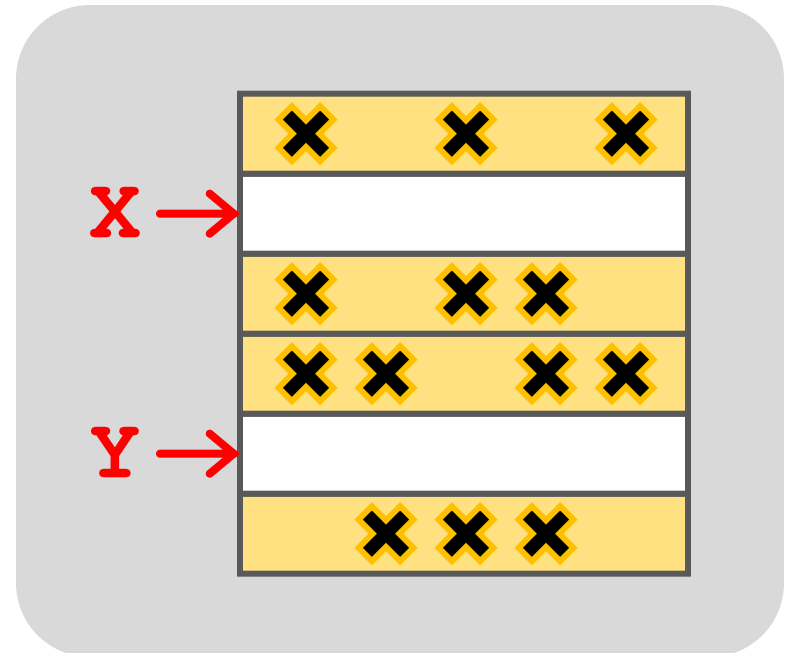
```
loop:  
  mov  (X), %eax  
  mov  (Y), %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



A Simple Program Can Induce Many Errors



```
loop:  
  mov  (X),  %eax  
  mov  (Y),  %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



Observed Errors in Real Systems

| CPU Architecture | Errors | Access-Rate |
|---------------------------|--------|-------------|
| Intel Haswell (2013) | 22.9K | 12.3M/sec |
| Intel Ivy Bridge (2012) | 20.7K | 11.7M/sec |
| Intel Sandy Bridge (2011) | 16.1K | 11.6M/sec |
| AMD Piledriver (2012) | 59 | 6.1M/sec |

A real reliability, security, safety issue

One Can Take Over an Otherwise-Secure System

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Abstract. Memory isolation is a key property of a reliable and secure computing system — an access to one memory address should not have unintended side effects on data stored in other addresses. However, as DRAM process technology

Project Zero

Flipping Bits in Memory Without Accessing Them:
An Experimental Study of DRAM Disturbance Errors
(Kim et al., ISCA 2014)

News and updates from the Project Zero team at Google

Exploiting the DRAM rowhammer bug to
gain kernel privileges (Seaborn, 2015)

Monday, March 9, 2015

Exploiting the DRAM rowhammer bug to gain kernel privileges

RowHammer Security Attack Example

- “Rowhammer” is a problem with some recent DRAM devices in which repeatedly accessing a row of memory can cause bit flips in adjacent rows (Kim et al., ISCA 2014).
 - Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors (Kim et al., ISCA 2014)
- We tested a selection of laptops and found that a subset of them exhibited the problem.
- We built two working privilege escalation exploits that use this effect.
 - Exploiting the DRAM rowhammer bug to gain kernel privileges (Seaborn+, 2015)
- One exploit uses rowhammer-induced bit flips to gain kernel privileges on x86-64 Linux when run as an unprivileged userland process.
- When run on a machine vulnerable to the rowhammer problem, the process was able to induce bit flips in page table entries (PTEs).
- It was able to use this to gain write access to its own page table, and hence gain read-write access to all of physical memory.

Security Implications



Security Implications



It's like breaking into an apartment by repeatedly slamming a neighbor's door until the vibrations open the door you were after

More Security Implications (I)

“We can gain unrestricted access to systems of website visitors.”

www.iaik.tugraz.at ■

Not there yet, but ...



ROOT privileges for web apps!

29

Daniel Gruss (@lavados), Clémentine Maurice (@BloodyTangerine),
December 28, 2015 — 32c3, Hamburg, Germany



GATED
COMMUNITIES

Rowhammer.js: A Remote Software-Induced Fault Attack in JavaScript (DIMVA'16)

More Security Implications (II)

"Can gain control of a smart phone deterministically"



Drammer: Deterministic Rowhammer
Attacks on Mobile Platforms, CCS'16 38

More Security Implications (III)

- Using an integrated GPU in a mobile system to remotely escalate privilege via the WebGL interface. [IEEE S&P 2018](#)



TECHNICA

[BIZ & IT](#) [TECH](#) [SCIENCE](#) [POLICY](#) [CARS](#) [GAMING & CULTURE](#)

"GRAND PWINING UNIT" —

Drive-by Rowhammer attack uses GPU to compromise an Android phone

JavaScript based GLitch pwns browsers by flipping bits inside memory chips.

DAN GOODIN - 5/3/2018, 12:00 PM

Grand Pwning Unit: Accelerating Microarchitectural Attacks with the GPU

Pietro Frigo
Vrije Universiteit
Amsterdam
p.frigo@vu.nl

Cristiano Giuffrida
Vrije Universiteit
Amsterdam
giuffrida@cs.vu.nl

Herbert Bos
Vrije Universiteit
Amsterdam
herbertb@cs.vu.nl

Kaveh Razavi
Vrije Universiteit
Amsterdam
kaveh@cs.vu.nl

More Security Implications (IV)

- Rowhammer over RDMA (I) [USENIX ATC 2018](#)

 TECHNICA

[BIZ & IT](#) [TECH](#) [SCIENCE](#) [POLICY](#) [CARS](#) [GAMING & CULTURE](#)

THROWHAMMER —

Packets over a LAN are all it takes to trigger serious Rowhammer bit flips

The bar for exploiting potentially serious DDR weakness keeps getting lower.

DAN GOODIN - 5/10/2018, 5:26 PM

Throwhammer: Rowhammer Attacks over the Network and Defenses

Andrei Tatar
VU Amsterdam

Radhesh Krishnan
VU Amsterdam

Elias Athanasopoulos
University of Cyprus

Cristiano Giuffrida
VU Amsterdam

Herbert Bos
VU Amsterdam

Kaveh Razavi
VU Amsterdam

More Security Implications (V)

■ Rowhammer over RDMA (II)



Nethammer—Exploiting DRAM Rowhammer Bug Through Network Requests



Nethammer: Inducing Rowhammer Faults through Network Requests

Moritz Lipp
Graz University of Technology

Daniel Gruss
Graz University of Technology

Misiker Tadesse Aga
University of Michigan

Clémentine Maurice
Univ Rennes, CNRS, IRISA

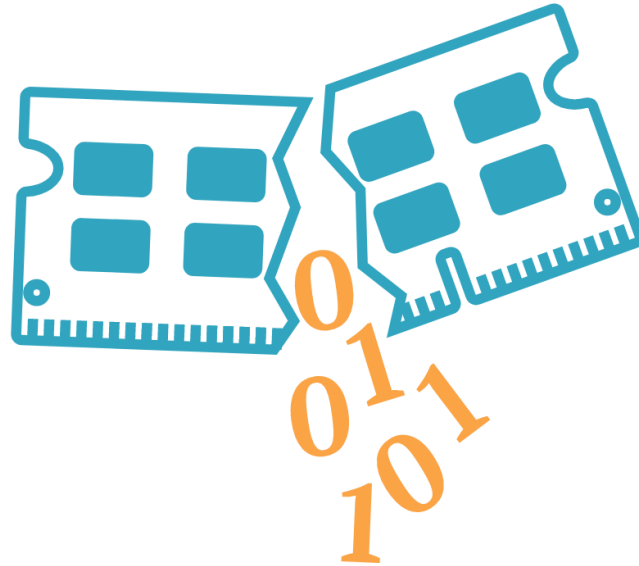
Michael Schwarz
Graz University of Technology

Lukas Raab
Graz University of Technology

Lukas Lamster
Graz University of Technology

More Security Implications (VI)

- IEEE S&P 2020



RAMBleed

RAMBleed: Reading Bits in Memory Without Accessing Them

Andrew Kwong
University of Michigan
ankwong@umich.edu

Daniel Genkin
University of Michigan
genkin@umich.edu

Daniel Gruss
Graz University of Technology
daniel.gruss@iaik.tugraz.at

Yuval Yarom
University of Adelaide and Data61
yval@cs.adelaide.edu.au

More Security Implications (VII)

■ USENIX Security 2019

Terminal Brain Damage: Exposing the Graceless Degradation in Deep Neural Networks Under Hardware Fault Attacks

Sanghyun Hong, Pietro Frigo[†], Yiğitcan Kaya, Cristiano Giuffrida[†], Tudor Dumitraş

University of Maryland, College Park

[†]Vrije Universiteit Amsterdam



A Single Bit-flip Can Cause Terminal Brain Damage to DNNs

One specific bit-flip in a DNN's representation leads to accuracy drop over 90%

Our research found that a specific bit-flip in a DNN's bitwise representation can cause the accuracy loss up to 90%, and the DNN has 40-50% parameters, on average, that can lead to the accuracy drop over 10% when individually subjected to such single bitwise corruptions...

[Read More](#)

More Security Implications (VIII)

■ USENIX Security 2020

DeepHammer: Depleting the Intelligence of Deep Neural Networks through Targeted Chain of Bit Flips

Fan Yao

University of Central Florida

fan.yao@ucf.edu

Adnan Siraj Rakin

Arizona State University

asrakin@asu.edu

Deliang Fan

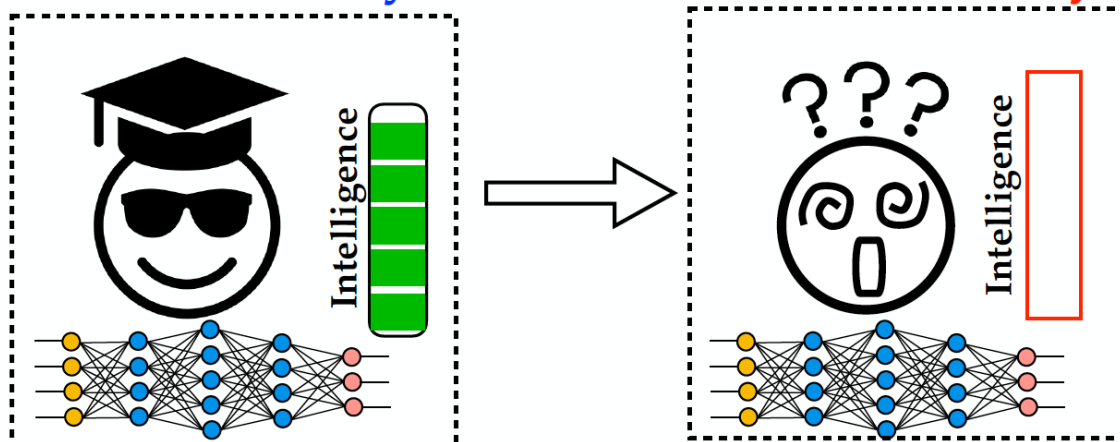
Arizona State University

dfan@asu.edu

Degrade the inference accuracy to the level of Random Guess

Example: ResNet-20 for CIFAR-10, 10 output classes

Before attack, **Accuracy: 90.2%** After attack, **Accuracy: ~10% (1/10)**



Google's Half-Double RowHammer Attack (May 2021)

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

Research Team: Salman Qazi, Yoongu Kim, Nicolas Boichat, Eric Shiu & Mattias Nissler

Today, we are sharing details around our discovery of [Half-Double](#), a new Rowhammer technique that capitalizes on the worsening physics of some of the newer DRAM chips to alter the contents of memory.

Rowhammer is a DRAM vulnerability whereby repeated accesses to one address can tamper with the data stored at other addresses. Much like speculative execution vulnerabilities in CPUs, Rowhammer is a breach of the security guarantees made by the underlying hardware. As an electrical coupling phenomenon within the silicon itself, Rowhammer allows the potential bypass of hardware and software memory protection policies. This can allow untrusted code to break out of its sandbox and take full control of the system.

More Security Implications (VIII)

- **USENIX Security 2022**
- **Google's Half-Double RowHammer Attack**

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

Research Team: Salman Qazi, Yoongu Kim, Nicolas Boichat, Eric Shiu & Mattias Nissler

Today, we are sharing details around our discovery of [Half-Double](#), a new Rowhammer technique that capitalizes on the worsening physics of some of the newer DRAM chips to alter the contents of memory.

Rowhammer is a DRAM vulnerability whereby repeated accesses to one address can tamper with the data stored at other addresses. Much like speculative execution vulnerabilities in CPUs, Rowhammer is a breach of the security guarantees made by the underlying hardware. As an electrical coupling phenomenon within the silicon itself, Rowhammer allows the potential bypass of hardware and software memory protection policies. This can allow untrusted code to break out of its sandbox and take full control of the system.

Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

¹*Graz University of Technology* ²*Lamarr Security Research* ³*Google*
⁴*Amazon Web Services* ⁵*Rivos*

More Security Implications?



A RowHammer Survey Across the Stack

- Onur Mutlu and Jeremie Kim,
["RowHammer: A Retrospective"](#)
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD) Special Issue on Top Picks in Hardware and Embedded Security, 2019.
[[Preliminary arXiv version](#)]
[[Slides from COSADE 2019 \(pptx\)](#)]
[[Slides from VLSI-SOC 2020 \(pptx\) \(pdf\)](#)]
[[Talk Video](#) (1 hr 15 minutes, with Q&A)]

RowHammer: A Retrospective

Onur Mutlu^{§‡} Jeremie S. Kim^{‡§}
§ETH Zürich ‡Carnegie Mellon University

A RowHammer Survey: Recent Update

- Onur Mutlu, Ataberk Olgun, and A. Giray Yaglikci,
"Fundamentally Understanding and Solving RowHammer"
Invited Special Session Paper at the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Tokyo, Japan, January 2023.
[arXiv version]
[Slides (pptx) (pdf)]
[Talk Video (26 minutes)]

Fundamentally Understanding and Solving RowHammer

Onur Mutlu
onur.mutlu@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

Ataberk Olgun
ataberk.olgund@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

A. Giray Yağlıkçı
giray.yaglikci@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

<https://arxiv.org/pdf/2211.07613.pdf>

Understanding RowHammer

First RowHammer Analysis [ISCA 2014]

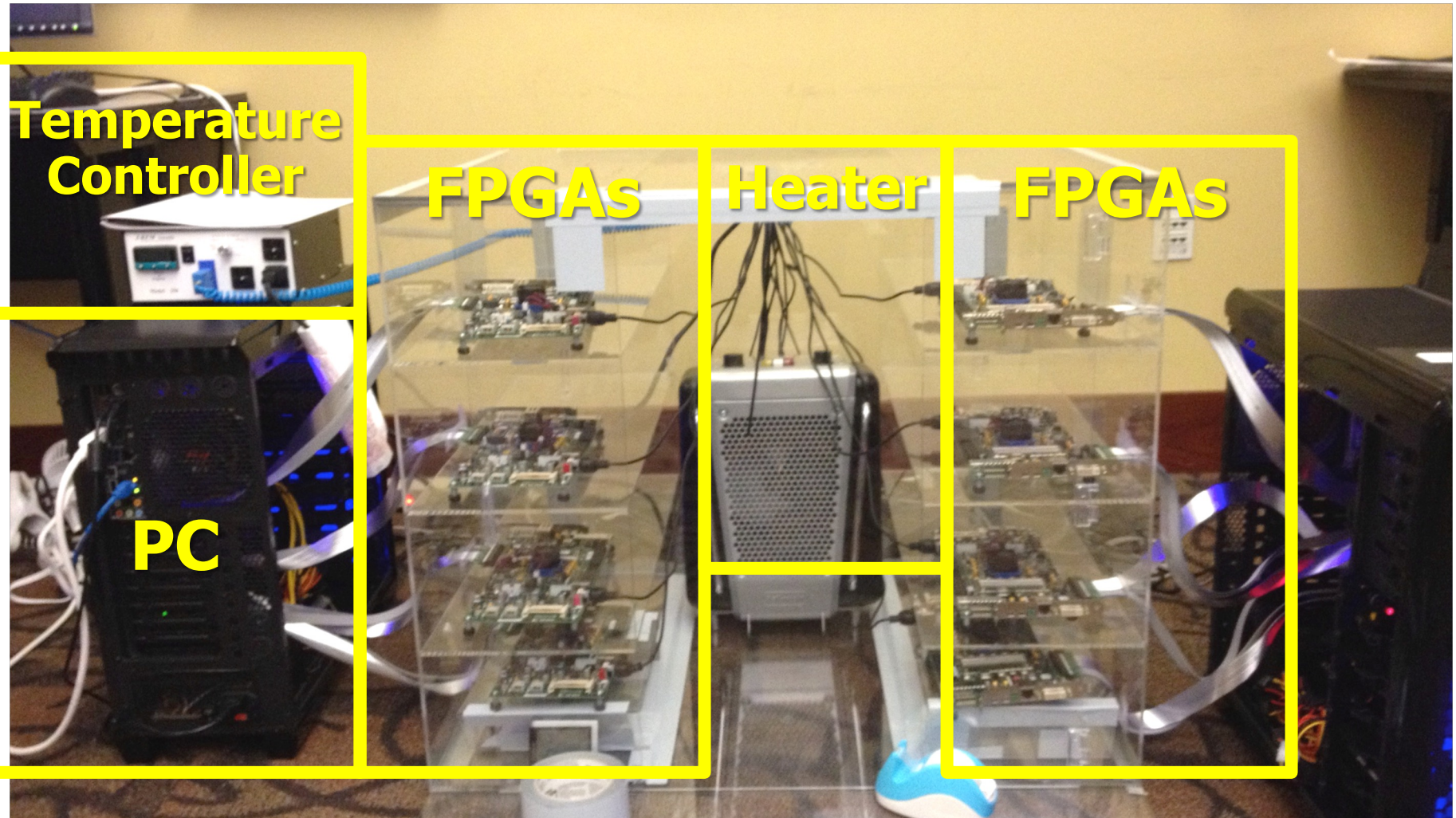
- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
Proceedings of the 41st International Symposium on Computer Architecture (ISCA), Minneapolis, MN, June 2014.
[Slides (pptx) (pdf)] [Lightning Session Slides (pptx) (pdf)] [Source Code and Data] [Lecture Video (1 hr 49 mins), 25 September 2020]
One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD ([link](#)).
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 ([Retrospective \(pdf\)](#) [Full Issue](#)).

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Yoongu Kim¹ Ross Daly* Jeremie Kim¹ Chris Fallin* Ji Hye Lee¹
Donghyuk Lee¹ Chris Wilkerson² Konrad Lai Onur Mutlu¹

¹Carnegie Mellon University ²Intel Labs

RowHammer Infrastructure (2012-2014)



Tested DRAM Modules from 2008-2014 (129 total)

| Manufacturer | Module | Date* | Timing† | | Organization | | Chip | | | Victims-per-Module | | | RI _{th} (ms) |
|---------------------|--------------------|---------|-------------|----------------------|--------------|-------|------------|------|-----------------------|-----------------------|-----------------------|---------|-----------------------|
| | | (yy-ww) | Freq (MT/s) | t _{RC} (ns) | Size (GB) | Chips | Size (Gb)‡ | Pins | DieVersion§ | Average | Minimum | Maximum | Min |
| Total of 43 Modules | A ₁ | 10-08 | 1066 | 50.625 | 0.5 | 4 | 1 × 16 | B | 0 | 0 | 0 | – | |
| | A ₂ | 10-20 | 1066 | 50.625 | 1 | 8 | 1 × 8 | F | 0 | 0 | 0 | – | |
| | A ₃₋₅ | 10-20 | 1066 | 50.625 | 0.5 | 4 | 1 × 16 | B | 0 | 0 | 0 | – | |
| | A ₆₋₇ | 11-24 | 1066 | 49.125 | 1 | 4 | 2 × 16 | D | 7.8 × 10 ¹ | 5.2 × 10 ¹ | 1.0 × 10 ² | 21.3 | |
| | A ₈₋₁₂ | 11-26 | 1066 | 49.125 | 1 | 4 | 2 × 16 | D | 2.4 × 10 ² | 5.4 × 10 ¹ | 4.4 × 10 ² | 16.4 | |
| | A ₁₃₋₁₄ | 11-50 | 1066 | 49.125 | 1 | 4 | 2 × 16 | D | 8.8 × 10 ¹ | 1.7 × 10 ¹ | 1.6 × 10 ² | 26.2 | |
| | A ₁₅₋₁₆ | 12-22 | 1600 | 50.625 | 1 | 4 | 2 × 16 | D | 9.5 | 9 | 1.0 × 10 ¹ | 34.4 | |
| | A ₁₇₋₁₈ | 12-26 | 1600 | 49.125 | 2 | 8 | 2 × 8 | M | 1.2 × 10 ² | 3.7 × 10 ¹ | 2.0 × 10 ² | 21.3 | |
| | A ₁₉₋₃₀ | 12-40 | 1600 | 48.125 | 2 | 8 | 2 × 8 | K | 8.6 × 10 ⁶ | 7.0 × 10 ⁶ | 1.0 × 10 ⁷ | 8.2 | |
| | A ₃₁₋₃₄ | 13-02 | 1600 | 48.125 | 2 | 8 | 2 × 8 | – | 1.8 × 10 ⁶ | 1.0 × 10 ⁶ | 3.5 × 10 ⁶ | 11.5 | |
| | A ₃₅₋₃₆ | 13-14 | 1600 | 48.125 | 2 | 8 | 2 × 8 | – | 4.0 × 10 ¹ | 1.9 × 10 ¹ | 6.1 × 10 ¹ | 21.3 | |
| | A ₃₇₋₃₈ | 13-20 | 1600 | 48.125 | 2 | 8 | 2 × 8 | K | 1.7 × 10 ⁶ | 1.4 × 10 ⁶ | 2.0 × 10 ⁶ | 9.8 | |
| | A ₃₉₋₄₀ | 13-28 | 1600 | 48.125 | 2 | 8 | 2 × 8 | K | 5.7 × 10 ⁴ | 5.4 × 10 ⁴ | 6.0 × 10 ⁴ | 16.4 | |
| | A ₄₁ | 14-04 | 1600 | 49.125 | 2 | 8 | 2 × 8 | – | 2.7 × 10 ⁵ | 2.7 × 10 ⁵ | 2.7 × 10 ⁵ | 18.0 | |
| | A ₄₂₋₄₃ | 14-04 | 1600 | 48.125 | 2 | 8 | 2 × 8 | K | 0.5 | 0 | 1 | 62.3 | |
| Total of 54 Modules | B ₁ | 08-49 | 1066 | 50.625 | 1 | 8 | 1 × 8 | D | 0 | 0 | 0 | – | |
| | B ₂ | 09-49 | 1066 | 50.625 | 1 | 8 | 1 × 8 | E | 0 | 0 | 0 | – | |
| | B ₃ | 10-19 | 1066 | 50.625 | 1 | 8 | 1 × 8 | F | 0 | 0 | 0 | – | |
| | B ₄ | 10-31 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 0 | 0 | 0 | – | |
| | B ₅ | 11-13 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 0 | 0 | 0 | – | |
| | B ₆ | 11-16 | 1066 | 50.625 | 1 | 8 | 1 × 8 | F | 0 | 0 | 0 | – | |
| | B ₇ | 11-19 | 1066 | 50.625 | 1 | 8 | 1 × 8 | F | 0 | 0 | 0 | – | |
| | B ₈ | 11-25 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 0 | 0 | 0 | – | |
| | B ₉ | 11-37 | 1333 | 49.125 | 2 | 8 | 2 × 8 | D | 1.9 × 10 ⁶ | 1.9 × 10 ⁶ | 1.9 × 10 ⁶ | 11.5 | |
| | B ₁₀₋₁₂ | 11-46 | 1333 | 49.125 | 2 | 8 | 2 × 8 | D | 2.2 × 10 ⁶ | 1.5 × 10 ⁶ | 2.7 × 10 ⁶ | 11.5 | |
| | B ₁₃ | 11-49 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 0 | 0 | 0 | – | |
| | B ₁₄ | 12-01 | 1866 | 47.125 | 2 | 8 | 2 × 8 | D | 9.1 × 10 ⁵ | 9.1 × 10 ⁵ | 9.1 × 10 ⁵ | 9.8 | |
| | B ₁₅₋₃₁ | 12-10 | 1866 | 47.125 | 2 | 8 | 2 × 8 | D | 9.8 × 10 ⁵ | 7.8 × 10 ⁵ | 1.2 × 10 ⁶ | 11.5 | |
| | B ₃₂ | 12-25 | 1600 | 48.125 | 2 | 8 | 2 × 8 | E | 7.4 × 10 ⁵ | 7.4 × 10 ⁵ | 7.4 × 10 ⁵ | 11.5 | |
| | B ₃₃₋₄₂ | 12-28 | 1600 | 48.125 | 2 | 8 | 2 × 8 | E | 5.2 × 10 ⁵ | 1.9 × 10 ⁵ | 7.3 × 10 ⁵ | 11.5 | |
| Total of 32 Modules | C ₁ | 10-18 | 1333 | 49.125 | 2 | 8 | 2 × 8 | A | 0 | 0 | 0 | – | |
| | C ₂ | 10-20 | 1066 | 50.625 | 2 | 8 | 2 × 8 | A | 0 | 0 | 0 | – | |
| | C ₃ | 10-22 | 1066 | 50.625 | 2 | 8 | 2 × 8 | A | 0 | 0 | 0 | – | |
| | C ₄₋₅ | 10-26 | 1333 | 49.125 | 2 | 8 | 2 × 8 | B | 8.9 × 10 ² | 6.0 × 10 ² | 1.2 × 10 ³ | 29.5 | |
| | C ₆ | 10-43 | 1333 | 49.125 | 1 | 8 | 1 × 8 | T | 0 | 0 | 0 | – | |
| | C ₇ | 10-51 | 1333 | 49.125 | 2 | 8 | 2 × 8 | B | 4.0 × 10 ² | 4.0 × 10 ² | 4.0 × 10 ² | 29.5 | |
| | C ₈ | 11-12 | 1333 | 46.25 | 2 | 8 | 2 × 8 | B | 6.9 × 10 ² | 6.9 × 10 ² | 6.9 × 10 ² | 21.3 | |
| | C ₉ | 11-19 | 1333 | 46.25 | 2 | 8 | 2 × 8 | B | 9.2 × 10 ² | 9.2 × 10 ² | 9.2 × 10 ² | 27.9 | |
| | C ₁₀ | 11-31 | 1333 | 49.125 | 2 | 8 | 2 × 8 | B | 3 | 3 | 3 | 39.3 | |
| | C ₁₁ | 11-42 | 1333 | 49.125 | 2 | 8 | 2 × 8 | B | 1.6 × 10 ² | 1.6 × 10 ² | 1.6 × 10 ² | 39.3 | |
| | C ₁₂ | 11-48 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 7.1 × 10 ⁴ | 7.1 × 10 ⁴ | 7.1 × 10 ⁴ | 19.7 | |
| | C ₁₃ | 12-08 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 3.9 × 10 ⁴ | 3.9 × 10 ⁴ | 3.9 × 10 ⁴ | 21.3 | |
| | C ₁₄₋₁₅ | 12-12 | 1333 | 49.125 | 2 | 8 | 2 × 8 | C | 3.7 × 10 ⁴ | 2.1 × 10 ⁴ | 5.4 × 10 ⁴ | 21.3 | |
| | C ₁₆₋₁₈ | 12-20 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 3.5 × 10 ³ | 1.2 × 10 ³ | 7.0 × 10 ³ | 27.9 | |
| | C ₁₉ | 12-23 | 1600 | 48.125 | 2 | 8 | 2 × 8 | E | 1.4 × 10 ⁵ | 1.4 × 10 ⁵ | 1.4 × 10 ⁵ | 18.0 | |
| | C ₂₀ | 12-24 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 6.5 × 10 ⁴ | 6.5 × 10 ⁴ | 6.5 × 10 ⁴ | 21.3 | |
| | C ₂₁ | 12-26 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 2.3 × 10 ⁴ | 2.3 × 10 ⁴ | 2.3 × 10 ⁴ | 24.6 | |
| | C ₂₂ | 12-32 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 1.7 × 10 ⁴ | 1.7 × 10 ⁴ | 1.7 × 10 ⁴ | 22.9 | |
| | C ₂₃₋₂₄ | 12-37 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 2.3 × 10 ⁴ | 1.1 × 10 ⁴ | 3.4 × 10 ⁴ | 18.0 | |
| | C ₂₅₋₃₀ | 12-41 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 2.0 × 10 ⁴ | 1.1 × 10 ⁴ | 3.2 × 10 ⁴ | 19.7 | |
| | C ₃₁ | 13-11 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 3.3 × 10 ⁵ | 3.3 × 10 ⁵ | 3.3 × 10 ⁵ | 14.7 | |
| | C ₃₂ | 13-35 | 1600 | 48.125 | 2 | 8 | 2 × 8 | C | 3.7 × 10 ⁴ | 3.7 × 10 ⁴ | 3.7 × 10 ⁴ | 21.3 | |

* We report the manufacture date marked on the chip packages, which is more accurate than other dates that can be gleaned from a module.

† We report timing constraints stored in the module's on-board ROM [33], which is read by the system BIOS to calibrate the memory controller.

‡ The maximum DRAM chip size supported by our testing platform is 2Gb.

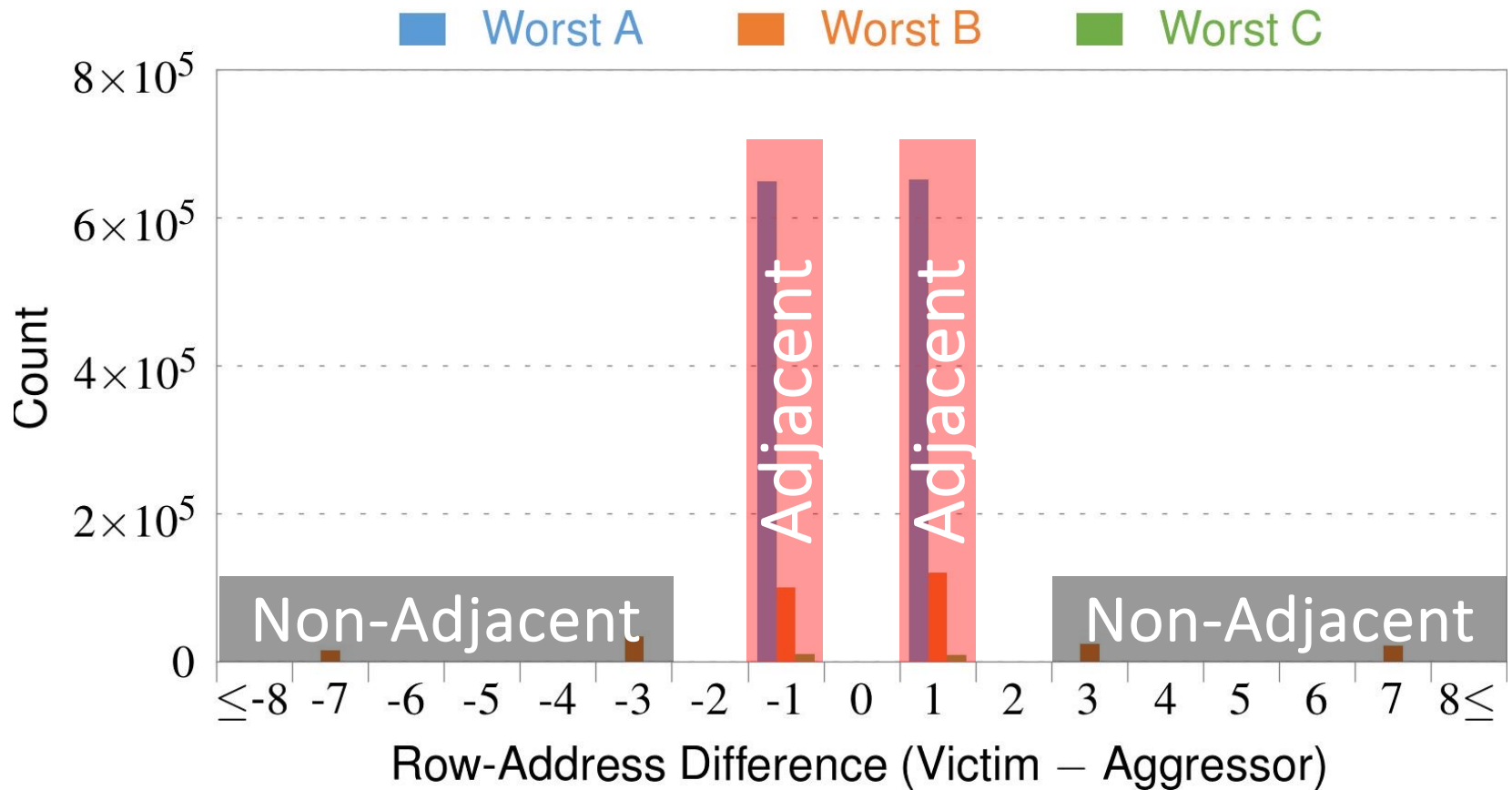
§ We report DRAM die versions marked on the chip packages, which typically progress in the following manner: $\mathcal{M} \rightarrow \mathcal{A} \rightarrow \mathcal{B} \rightarrow \mathcal{C} \rightarrow \dots$.

Table 3. Sample population of 129 DDR3 DRAM modules, categorized by manufacturer and sorted by manufacture date

RowHammer Characterization Results

1. Most Modules Are at Risk
2. Errors vs. Vintage
3. Error = Charge Loss
4. Adjacency: Aggressor & Victim
5. Sensitivity Studies
6. Other Results in Paper
7. Solution Space

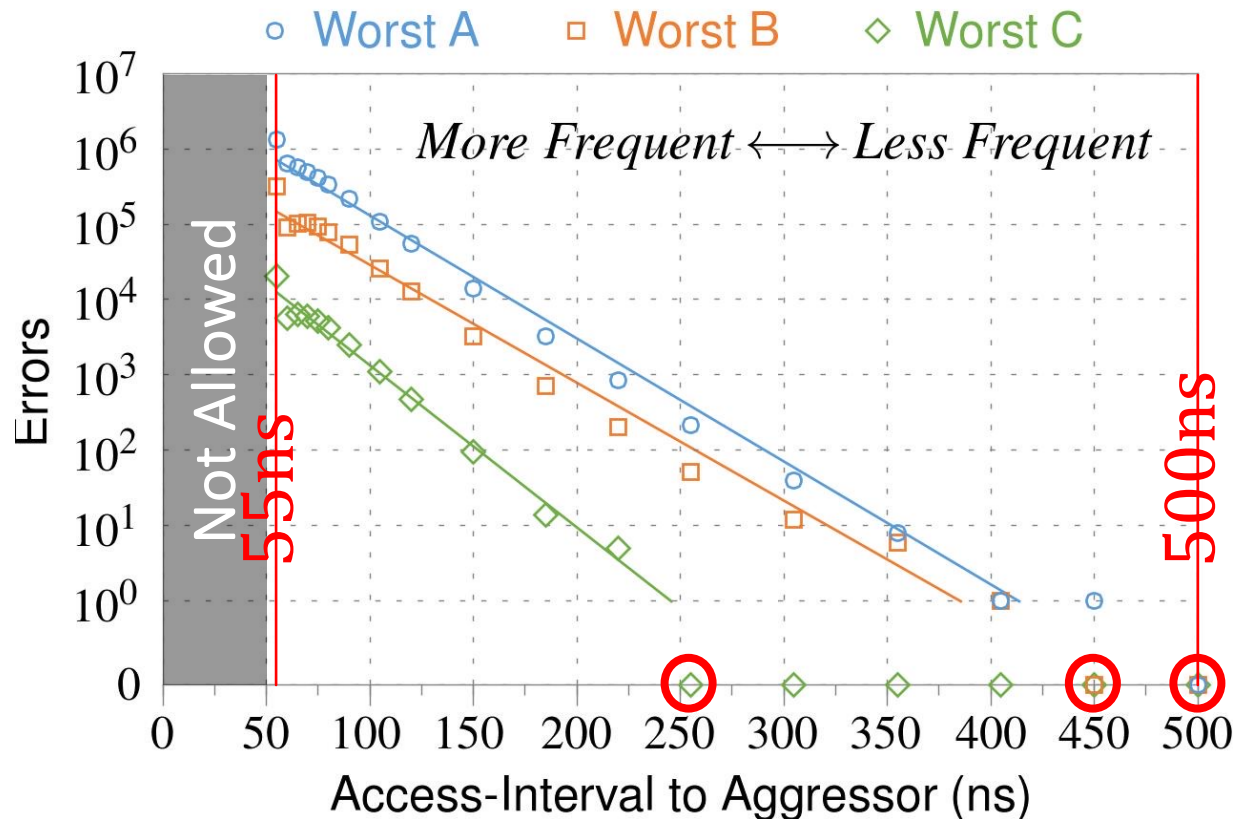
4. Adjacency: Aggressor & Victim



Note: For three modules with the most errors (only first bank)

Most aggressors & victims are adjacent

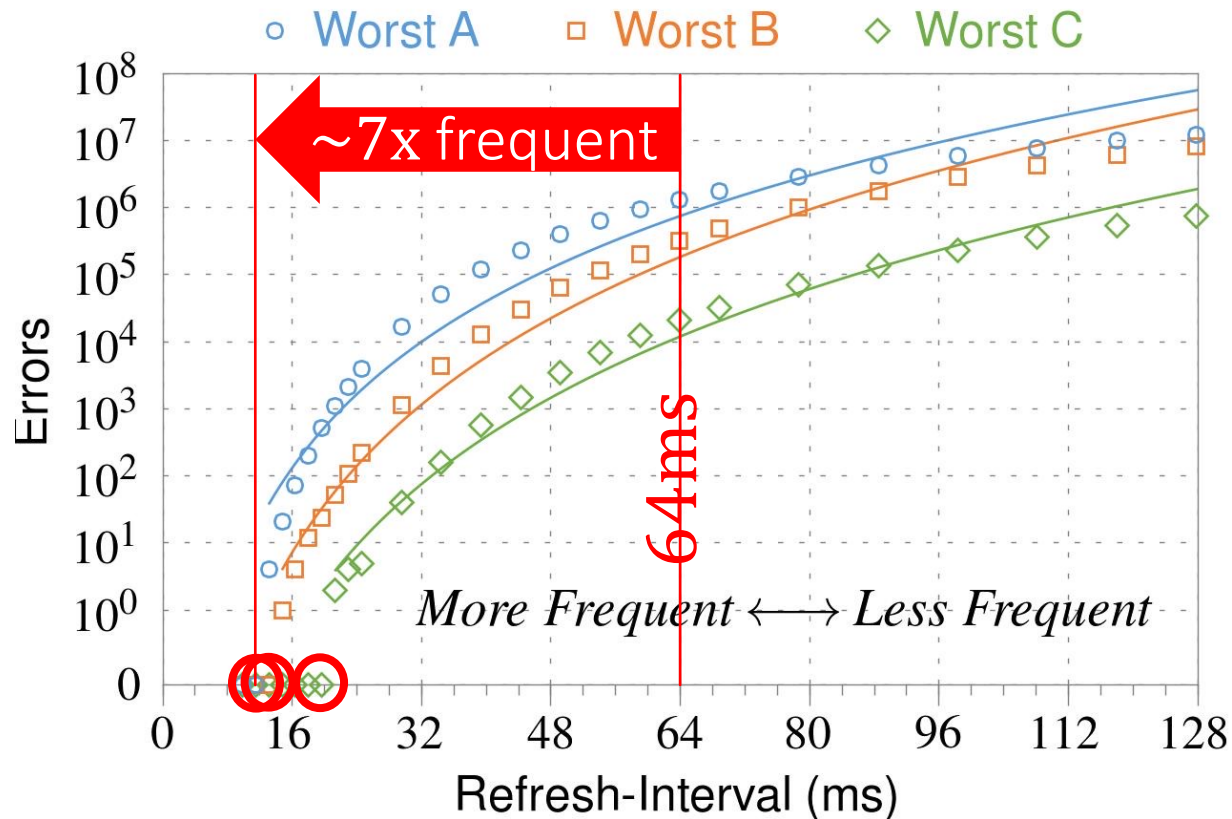
① Access Interval (Aggressor)



Note: For three modules with the most errors (only first bank)

Less frequent accesses \rightarrow Fewer errors

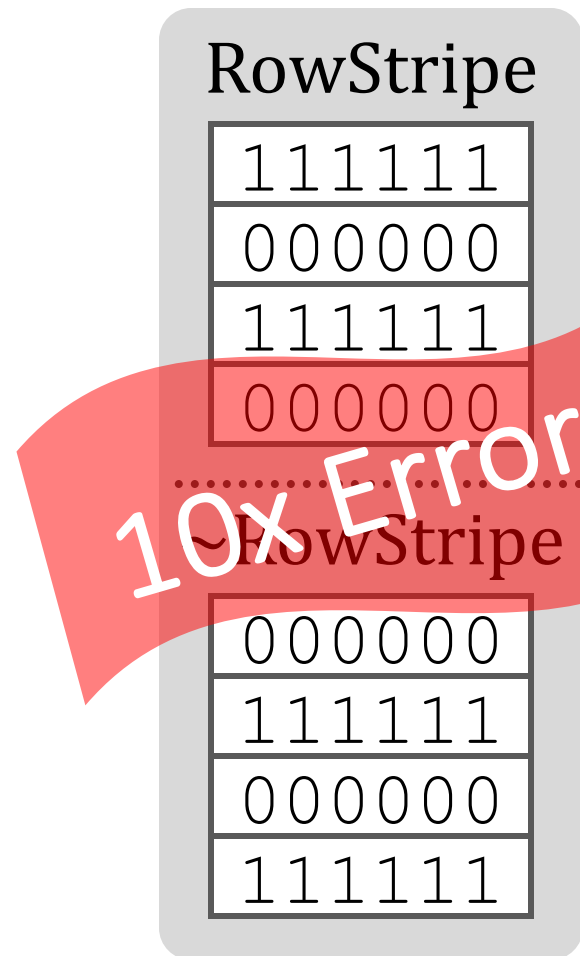
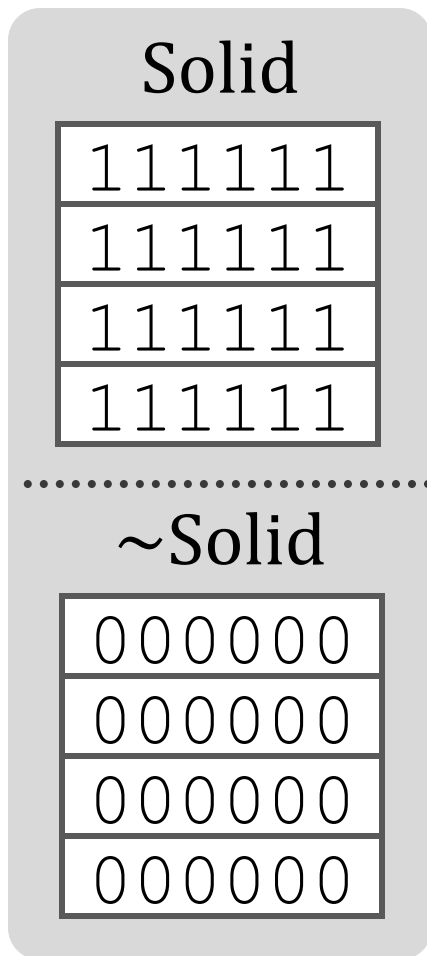
2 Refresh Interval



Note: Using three modules with the most errors (only first bank)

More frequent refreshes \rightarrow Fewer errors

3 Data Pattern



10x Errors

Errors affected by data stored in other cells

6. Other Key Observations [ISCA'14]

- *Victim Cells \neq Retention-Weak Cells*
 - Almost no overlap between them
- *Errors are repeatable*
 - Across ten iterations of testing, >70% of victim cells had errors in every iteration
- *As many as 4 errors per cache-line*
 - Simple ECC (e.g., SECDED) cannot prevent all errors
- *Cells affected by two aggressors on either side*
 - Double sided hammering

Major RowHammer Characteristics (2014)

- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
Proceedings of the 41st International Symposium on Computer Architecture (ISCA), Minneapolis, MN, June 2014.
[[Slides \(pptx\) \(pdf\)](#)] [[Lightning Session Slides \(pptx\) \(pdf\)](#)] [[Source Code and Data](#)] [[Lecture Video](#) (1 hr 49 mins), 25 September 2020]
One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD ([link](#)).
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 ([Retrospective \(pdf\)](#) [Full Issue](#)).

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Yoongu Kim¹ Ross Daly* Jeremie Kim¹ Chris Fallin* Ji Hye Lee¹
Donghyuk Lee¹ Chris Wilkerson² Konrad Lai Onur Mutlu¹

¹Carnegie Mellon University ²Intel Labs

RowHammer is Getting Much Worse (2020)

- Jeremie S. Kim, Minesh Patel, A. Giray Yaglikci, Hasan Hassan, Roknoddin Azizi, Lois Orosa, and Onur Mutlu,
["Revisiting RowHammer: An Experimental Analysis of Modern Devices and Mitigation Techniques"](#)
Proceedings of the 47th International Symposium on Computer Architecture (ISCA), Valencia, Spain, June 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (20 minutes)]
[[Lightning Talk Video](#) (3 minutes)]

Revisiting RowHammer: An Experimental Analysis of Modern DRAM Devices and Mitigation Techniques

Jeremie S. Kim^{§†} Minesh Patel[§] A. Giray Yağlıkçı[§]
Hasan Hassan[§] Roknoddin Azizi[§] Lois Orosa[§] Onur Mutlu^{§†}
[§]*ETH Zürich* [†]*Carnegie Mellon University*

RowHammer Has Many Dimensions (2021)

- Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo, Ataberk Olgun, Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, and Onur Mutlu,
"A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses"
*Proceedings of the 54th International Symposium on Microarchitecture (**MICRO**), Virtual, October 2021.*
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (21 minutes)]
[[Lightning Talk Video](#) (1.5 minutes)]
[[arXiv version](#)]

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa*
ETH Zürich

A. Giray Yağlıkçı*
ETH Zürich

Haocong Luo
ETH Zürich

Ataberk Olgun
ETH Zürich, TOBB ETÜ

Jisung Park
ETH Zürich

Hasan Hassan
ETH Zürich

Minesh Patel
ETH Zürich

Jeremie S. Kim
ETH Zürich

Onur Mutlu
ETH Zürich

RowHammer vs. Wordline Voltage (2022)

- A. Giray Yağlıkçı, Haocong Luo, Geraldo F. de Oliveira, Ataberk Olgun, Minesh Patel, Jisung Park, Hasan Hassan, Jeremie S. Kim, Lois Orosa, and Onur Mutlu, **"Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices"**
Proceedings of the 52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Baltimore, MD, USA, June 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[arXiv version](#)]
[[Talk Video](#) (34 minutes, including Q&A)]
[[Lightning Talk Video](#) (2 minutes)]

Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices

A. Giray Yağlıkçı¹ Haocong Luo¹ Geraldo F. de Oliveira¹ Ataberk Olgun¹ Minesh Patel¹
Jisung Park¹ Hasan Hassan¹ Jeremie S. Kim¹ Lois Orosa^{1,2} Onur Mutlu¹
¹*ETH Zürich* ²*Galicia Supercomputing Center (CESGA)*

RowHammer in HBM Chips (2023)

- Ataberk Olgun, Majd Osserian, A. Giray Yağlıkçı, Yahya Can Tugrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez-Luna, and Onur Mutlu, **"An Experimental Analysis of RowHammer in HBM2 DRAM Chips"**
Proceedings of the 53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Disrupt Track (DSN Disrupt), Porto, Portugal, June 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (24 minutes, including Q&A)]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran^{1,2} A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami¹ Juan Gomez Luna¹ Onur Mutlu¹
¹SAFARI Research Group, ETH Zürich ²American University of Beirut

RowHammer Solutions

Two Types of RowHammer Solutions

■ Immediate

- ❑ To protect the vulnerable DRAM chips in the field
- ❑ Limited possibilities

■ Longer-term

- ❑ To protect future DRAM chips
- ❑ Wider range of protection mechanisms

■ Our ISCA 2014 paper proposes both types of solutions

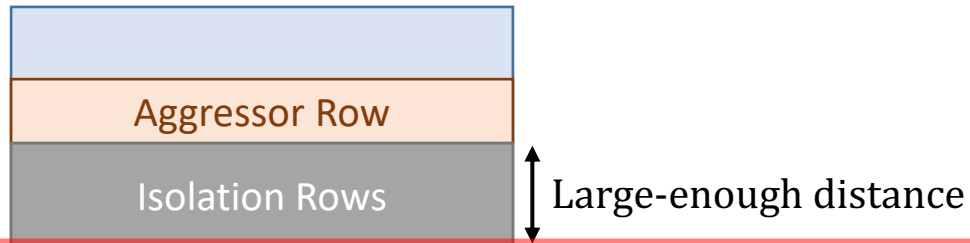
- ❑ Seven solutions in total
- ❑ PARA proposed as best solution → already employed in the field

RowHammer Solution Approaches

- More robust DRAM chips **and/or** error-correcting codes
- Increased refresh rate

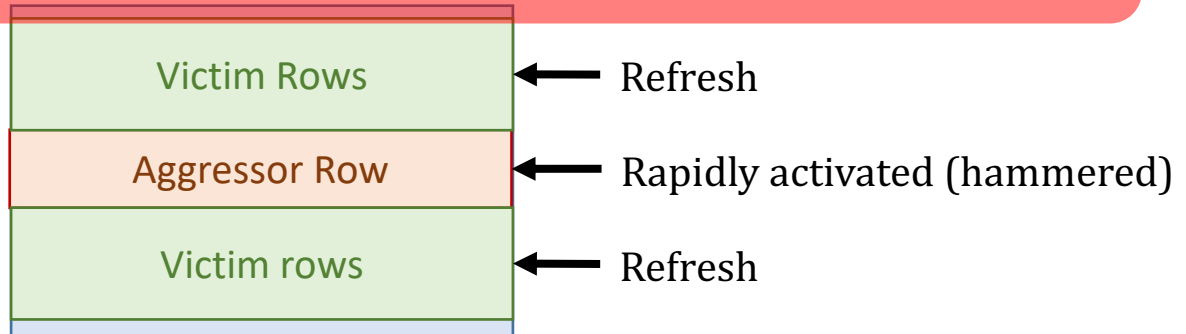


- Physical isolation



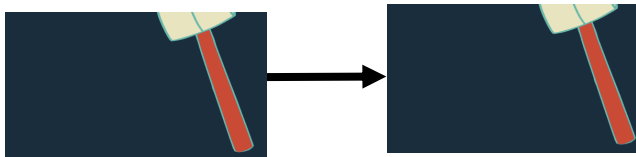
Cost, Power, Performance, Complexity

- Reactive refresh



- Proactive throttling

SAFARI



Fewer activations allowed for aggressive applications

Apple's Security Patch for RowHammer

- <https://support.apple.com/en-gb/HT204934>

Available for: OS X Mountain Lion v10.8.5, OS X Mavericks v10.9.5

Impact: A malicious application may induce memory corruption to escalate privileges

Description: A disturbance error, also known as Rowhammer, exists with some DDR3 RAM that could have led to memory corruption. This issue was mitigated by increasing memory refresh rates.

CVE-ID

CVE-2015-3693 : Mark Seaborn and Thomas Dullien of Google, working from original research by Yoongu Kim et al (2014)

HP, Lenovo, and many other vendors released similar patches

Our First Solution to RowHammer

- *PARA: Probabilistic Adjacent Row Activation*
- Key Idea
 - After closing a row, activate (i.e., refresh) its neighbors with a low probability: $p = 0.005$
- Reliability Guarantee
 - When $p=0.005$, errors in one year: 9.4×10^{-14}
 - By adjusting the value of p , we can vary the strength of protection against errors

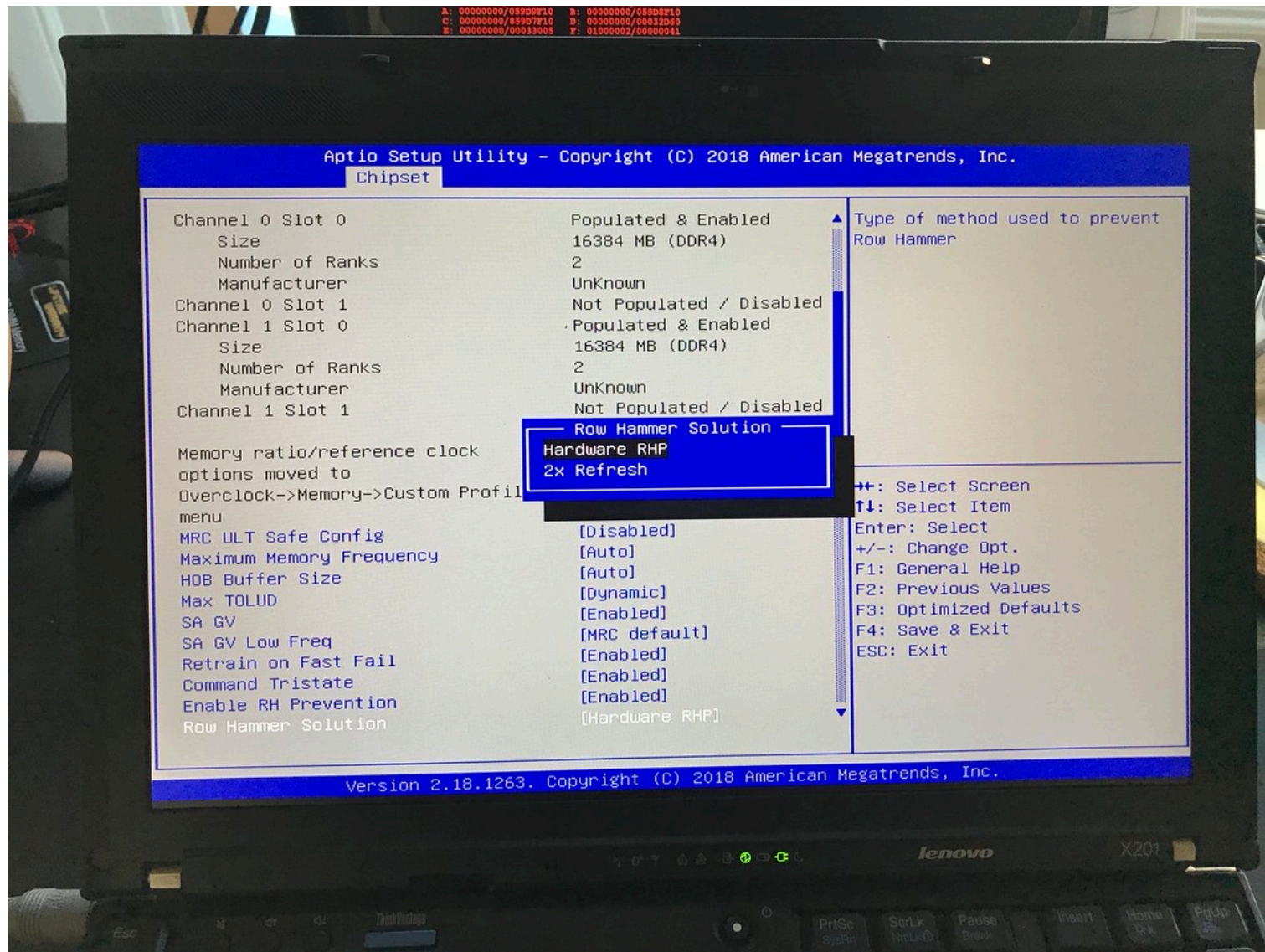
Advantages of PARA

- *PARA refreshes rows infrequently*
 - Low power
 - Low performance-overhead
 - Average slowdown: **0.20%** (for 29 benchmarks)
 - Maximum slowdown: **0.75%**
- *PARA is stateless*
 - Low cost
 - Low complexity
- *PARA is an effective and low-overhead solution to prevent disturbance errors*

Requirements for PARA

- If implemented in **DRAM chip** (done today)
 - Enough slack in timing and refresh parameters
 - Plenty of slack today:
 - Lee et al., “**Adaptive-Latency DRAM: Optimizing DRAM Timing for the Common Case**,” HPCA 2015.
 - Chang et al., “**Understanding Latency Variation in Modern DRAM Chips**,” SIGMETRICS 2016.
 - Lee et al., “**Design-Induced Latency Variation in Modern DRAM Chips**,” SIGMETRICS 2017.
 - Chang et al., “**Understanding Reduced-Voltage Operation in Modern DRAM Devices**,” SIGMETRICS 2017.
 - Ghose et al., “**What Your DRAM Power Models Are Not Telling You: Lessons from a Detailed Experimental Study**,” SIGMETRICS 2018.
 - Kim et al., “**Solar-DRAM: Reducing DRAM Access Latency by Exploiting the Variation in Local Bitlines**,” ICCD 2018.
- If implemented in **memory controller**
 - Need coordination between controller and DRAM
 - Memory controller should know which rows are physically adjacent

Probabilistic Activation in Real Life (I)



Probabilistic Activation in Real Life (II)



Seven RowHammer Solutions Proposed

- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
Proceedings of the 41st International Symposium on Computer Architecture (ISCA), Minneapolis, MN, June 2014.
[\[Slides \(pptx\) \(pdf\)\]](#) [\[Lightning Session Slides \(pptx\) \(pdf\)\]](#) [\[Source Code and Data\]](#) [\[Lecture Video\]](#) (1 hr 49 mins), 25 September 2020]
One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD ([link](#)).
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 ([Retrospective \(pdf\)](#) [Full Issue](#)).

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Yoongu Kim¹ Ross Daly* Jeremie Kim¹ Chris Fallin* Ji Hye Lee¹
Donghyuk Lee¹ Chris Wilkerson² Konrad Lai Onur Mutlu¹

¹Carnegie Mellon University ²Intel Labs

Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

Aside: Intelligent Controller for NAND Flash



[DATE 2012, ICCD 2012, DATE 2013, ITJ 2013, ICCD 2013, SIGMETRICS 2014, HPCA 2015, DSN 2015, MSST 2015, JSAC 2016, HPCA 2017, DFRWS 2017, PIEEE 2017, HPCA 2018, SIGMETRICS 2018]

Cai+, "Error Characterization, Mitigation, and Recovery in Flash Memory Based Solid State Drives," Proc. IEEE 2017.



Proceedings of the IEEE, Sept. 2017



Error Characterization, Mitigation, and Recovery in Flash-Memory-Based Solid-State Drives

This paper reviews the most recent advances in solid-state drive (SSD) error characterization, mitigation, and data recovery techniques to improve both SSD's reliability and lifetime.

By YU CAI, SAUGATA GHOSE, ERICH F. HARATSCH, YIXIN LUO, AND ONUR MUTLU

<https://arxiv.org/pdf/1706.08642>

Two Major RowHammer Directions

■ **Understanding RowHammer**

- Many effects still need to be rigorously examined
 - Aging of DRAM Chips
 - Environmental Conditions (e.g., Process, Voltage, Temperature)
 - Memory Access Patterns
 - Memory Controller & System Design Decisions
 - ...

■ **Solving RowHammer**

- Flexible and efficient solutions are necessary
 - In-field patchable / reconfigurable / programmable solutions
- Co-architecting System and Memory is important
 - To avoid performance and denial-of-service problems

RowHammer in 2020-2024

Revisiting RowHammer

RowHammer is Getting Much Worse

- Jeremie S. Kim, Minesh Patel, A. Giray Yaglikci, Hasan Hassan, Roknoddin Azizi, Lois Orosa, and Onur Mutlu,
"Revisiting RowHammer: An Experimental Analysis of Modern Devices and Mitigation Techniques"
Proceedings of the 47th International Symposium on Computer Architecture (ISCA), Valencia, Spain, June 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (20 minutes)]
[[Lightning Talk Video](#) (3 minutes)]

Revisiting RowHammer: An Experimental Analysis of Modern DRAM Devices and Mitigation Techniques

Jeremie S. Kim^{§†} Minesh Patel[§] A. Giray Yağlıkçı[§]
Hasan Hassan[§] Roknoddin Azizi[§] Lois Orosa[§] Onur Mutlu^{§†}
[§]*ETH Zürich* [†]*Carnegie Mellon University*

Key Takeaways from 1580 Chips

- **Newer DRAM chips are much more vulnerable to RowHammer (more bit flips, happening earlier)**
- There are new chips whose weakest cells fail after **only 4800 hammers**
- Chips of newer DRAM technology nodes can exhibit RowHammer bit flips 1) in **more rows** and 2) **farther away** from the victim row.
- **Existing mitigation mechanisms are NOT effective at future technology nodes**

1580 DRAM Chips Tested

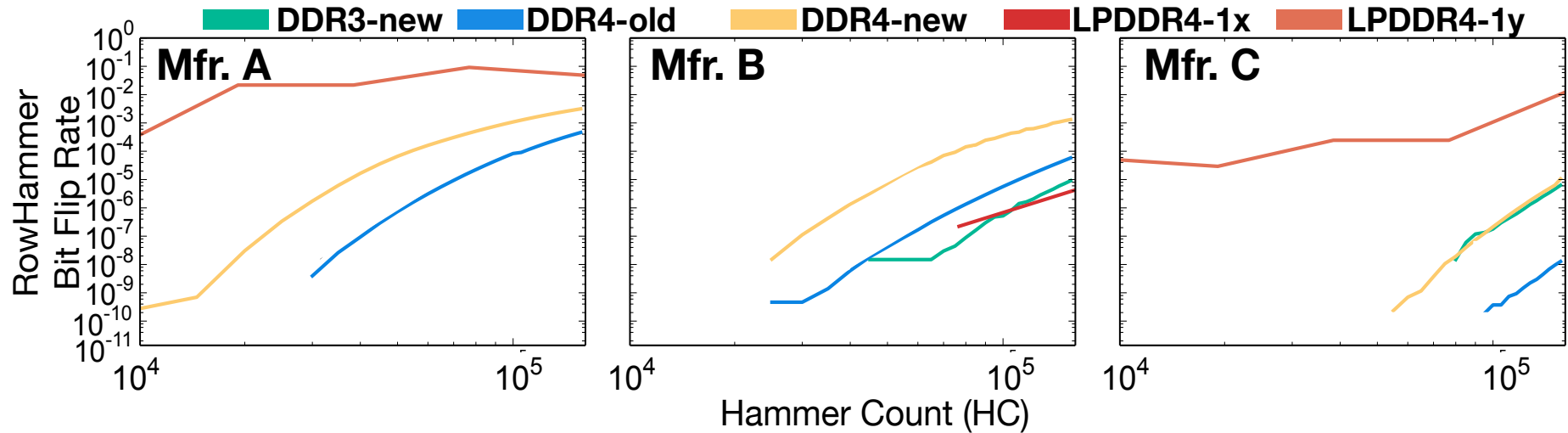
| DRAM type-node | Number of Chips (Modules) Tested | | | |
|-------------------|----------------------------------|----------|----------|----------|
| | Mfr. A | Mfr. B | Mfr. C | Total |
| DDR3-old | 56 (10) | 88 (11) | 28 (7) | 172 (28) |
| DDR3-new | 80 (10) | 52 (9) | 104 (13) | 236 (32) |
| DDR4-old | 112 (16) | 24 (3) | 128 (18) | 264 (37) |
| DDR4-new | 264 (43) | 16 (2) | 108 (28) | 388 (73) |
| LPDDR4-1x | 12 (3) | 180 (45) | N/A | 192 (48) |
| LPDDR4-1y | 184 (46) | N/A | 144 (36) | 328 (82) |

1580 total DRAM chips tested from **300** DRAM modules

- **Three** major DRAM manufacturers {A, B, C}
- **Three** DRAM *types or standards* {DDR3, DDR4, LPDDR4}
 - LPDDR4 chips we test implement on-die ECC
- **Two** technology nodes per DRAM type {old/new, 1x/1y}
 - Categorized based on manufacturing date, datasheet publication date, purchase date, and characterization results

Type-node: configuration describing a chip's type and technology node generation: **DDR3-old/new, DDR4-old/new, LPDDR4-1x/1y**

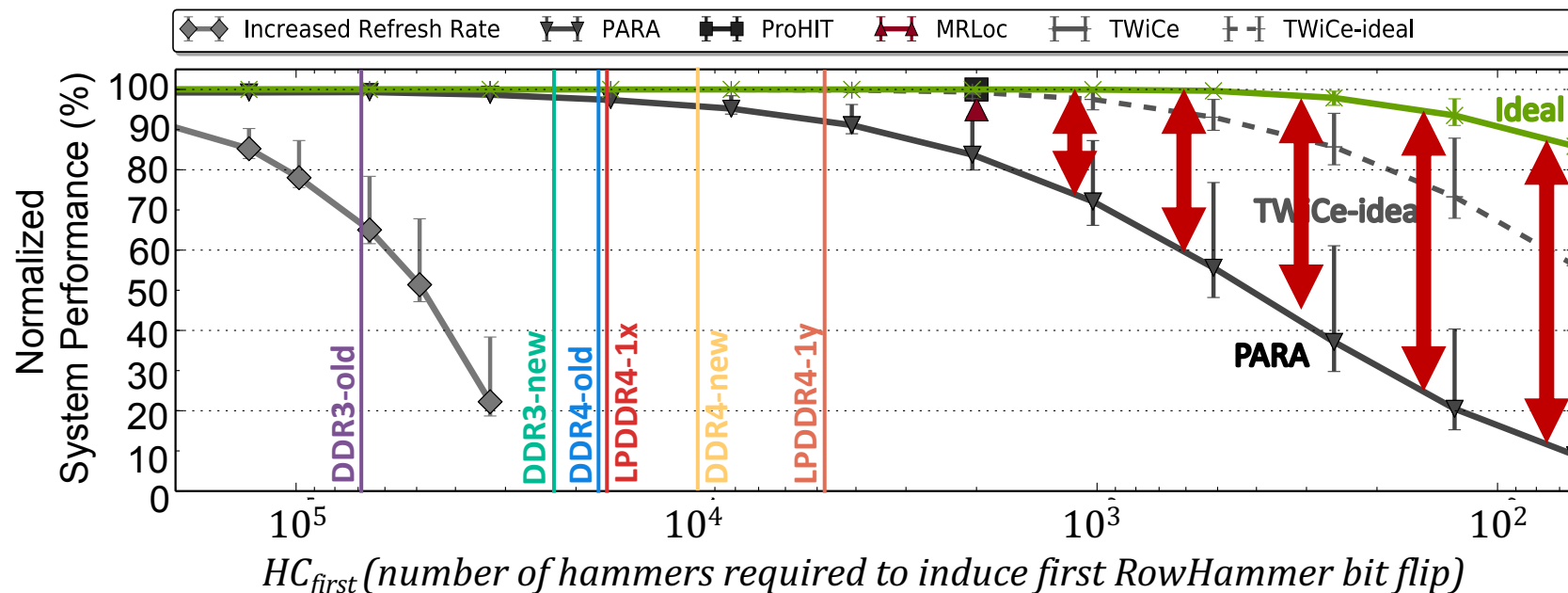
3. Hammer Count (HC) Effects



RowHammer bit flip rates **increase**
when going **from old to new** DDR4 technology node generations

**RowHammer bit flip rates (i.e., RowHammer vulnerability)
increase with technology node generation**

Mitigation Mechanism Evaluation



Ideal mechanism is **significantly better** than any existing mechanism for $HC_{first} < 1024$

Significant opportunity for developing a RowHammer solution with **low performance overhead** that supports low HC_{first}

New RowHammer Characteristics

RowHammer Has Many Dimensions

- Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo, Ataberk Olgun, Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, and Onur Mutlu,
"A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses"
*Proceedings of the 54th International Symposium on Microarchitecture (**MICRO**), Virtual, October 2021.*
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (21 minutes)]
[[Lightning Talk Video](#) (1.5 minutes)]
[[arXiv version](#)]

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa*
ETH Zürich

A. Giray Yağlıkçı*
ETH Zürich

Haocong Luo
ETH Zürich

Ataberk Olgun
ETH Zürich, TOBB ETÜ

Jisung Park
ETH Zürich

Hasan Hassan
ETH Zürich

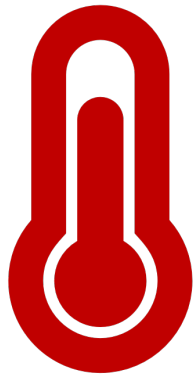
Minesh Patel
ETH Zürich

Jeremie S. Kim
ETH Zürich

Onur Mutlu
ETH Zürich

Our Goal

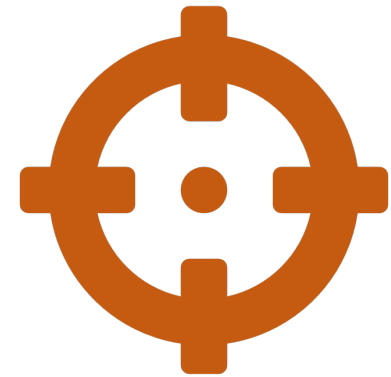
Provide insights into **three fundamental properties**



Temperature



Aggressor Row
Active Time



Victim DRAM Cell's
Physical Location

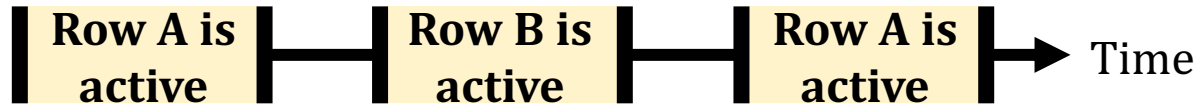
To find **effective and efficient** attacks and defenses

Summary of The Study & Key Results

- **272 DRAM chips** from **four major manufacturers**
- **6 major takeaways** from **16 novel observations**
- A RowHammer bit flip is **more likely to occur**
 - 1) in a **bounded range of temperature**
 - 2) if the aggressor row is **active for longer time**
 - 3) in **certain physical regions** of the DRAM module under attack
- Our novel observations can inspire and aid future work
 - Craft **more effective attacks**
 - Design **more effective and efficient defenses**

Example Attack Improvement 3: Bypassing Defenses with Aggressor Row Active Time

Activating aggressor rows as frequently as possible:



Keeping aggressor rows active for a longer time:

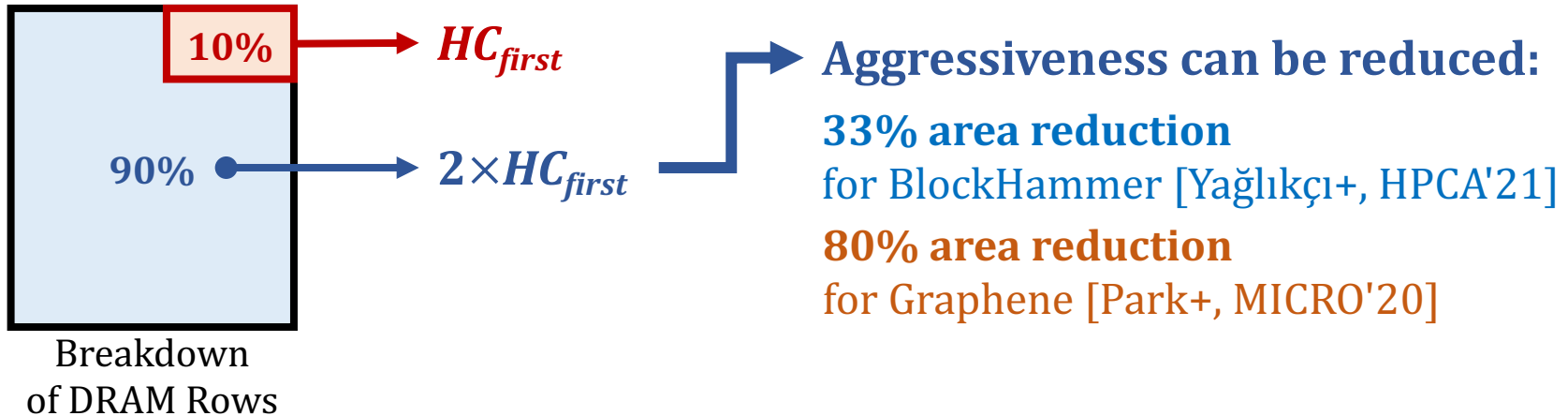


Reduces the minimum activation count to induce a bit flip **by 36%**

Bypasses defenses that do not account for this reduction

Example Defense Improvements

- **Example 1: Leveraging variation across DRAM rows**



- **Example 2: Leveraging variation with temperature**

- A DRAM cell experiences **bit flips** within a **bounded temperature range**




- A row can be **disabled** within the row's **vulnerable temperature range**




Deeper Look into RowHammer: Talk Video

Our Goal


Provide insights into **three fundamental properties**



Temperature



Aggressor Row
Active Time



Victim DRAM Cell's
Physical Location

To find **effective and efficient** attacks and defenses

SAFARI 4:11 / 21:25 • Motivation Goal >

ETH zürich
Gray Yaglici

A Deeper Look into RowHammer's Sensitivities: Analysis, Attacks & Defenses - MICRO'21 Long Talk; 21m

Onur Mutlu Lectures
31.6K subscribers

Analytics Edit video

16 Share Download Clip Save ...

More RowHammer Analysis

RowHammer vs. Wordline Voltage (2022)

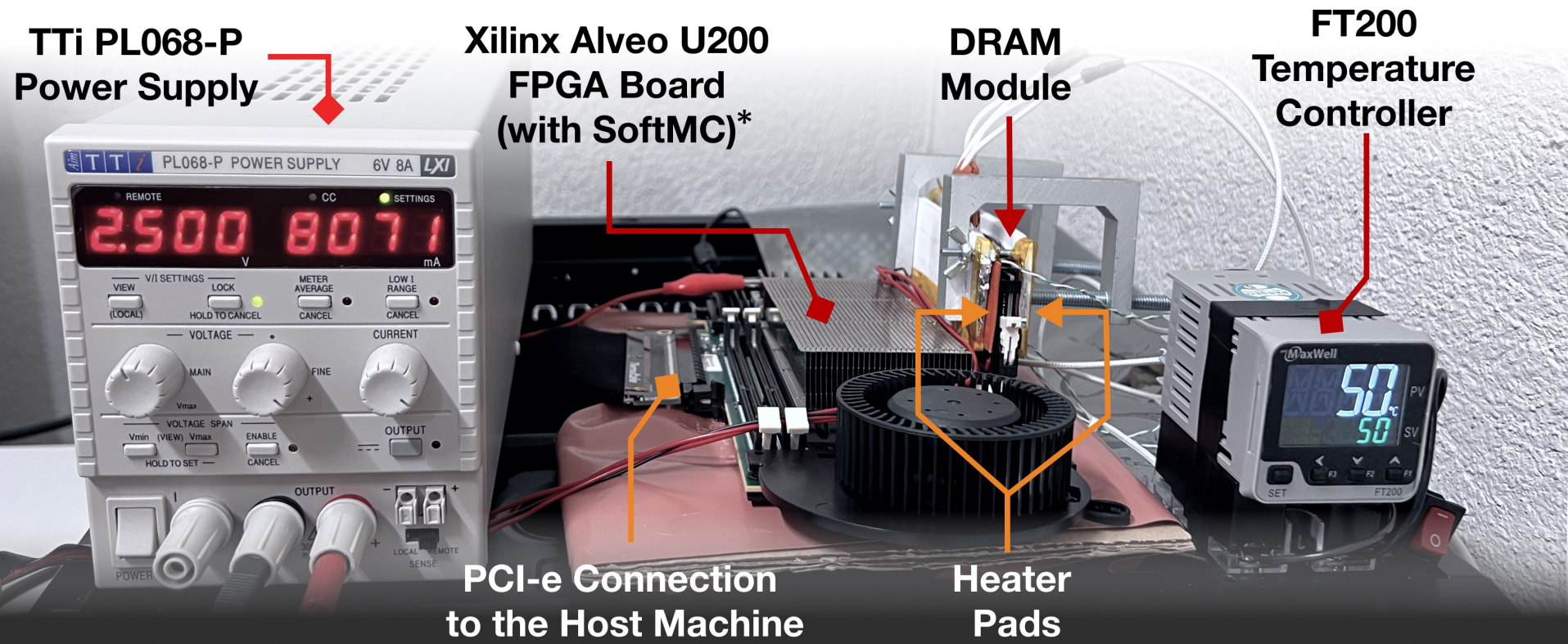
- A. Giray Yağlıkçı, Haocong Luo, Geraldo F. de Oliveira, Ataberk Olgun, Minesh Patel, Jisung Park, Hasan Hassan, Jeremie S. Kim, Lois Orosa, and Onur Mutlu, **"Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices"**
Proceedings of the 52nd Annual IEEE/IFIP International Conference on Dependable Systems and Networks (DSN), Baltimore, MD, USA, June 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[arXiv version](#)]
[[Talk Video](#) (34 minutes, including Q&A)]
[[Lightning Talk Video](#) (2 minutes)]

Understanding RowHammer Under Reduced Wordline Voltage: An Experimental Study Using Real DRAM Devices

A. Giray Yağlıkçı¹ Haocong Luo¹ Geraldo F. de Oliveira¹ Ataberk Olgun¹ Minesh Patel¹
Jisung Park¹ Hasan Hassan¹ Jeremie S. Kim¹ Lois Orosa^{1,2} Onur Mutlu¹
¹*ETH Zürich* ²*Galicia Supercomputing Center (CESGA)*

Updated DRAM Testing Infrastructure

FPGA-based SoftMC (Xilinx Virtex UltraScale+ XCU200)



Fine-grained control over DRAM commands,
timing parameters ($\pm 1.5\text{ns}$), temperature ($\pm 0.1^\circ\text{C}$),
and wordline voltage ($\pm 1\text{mV}$)

Summary

We provide *the first* RowHammer characterization **under reduced wordline voltage**

Experimental results with 272 *real DRAM chips* show that **reducing wordline voltage**:

1. Reduces RowHammer vulnerability

- **Bit error rate** caused by a RowHammer attack reduces by **15.2% (66.9% max)**
- A row needs to be activated **7.4% more times (85.8% max)** to induce *the first* bit flip

2. Increases row activation latency

- More than **76%** of the tested DRAM chips **reliably operate** using **nominal** timing parameters
- Remaining **24%** **reliably operate** with **increased** (up to 24ns) row activation latency

3. Reduces data retention time

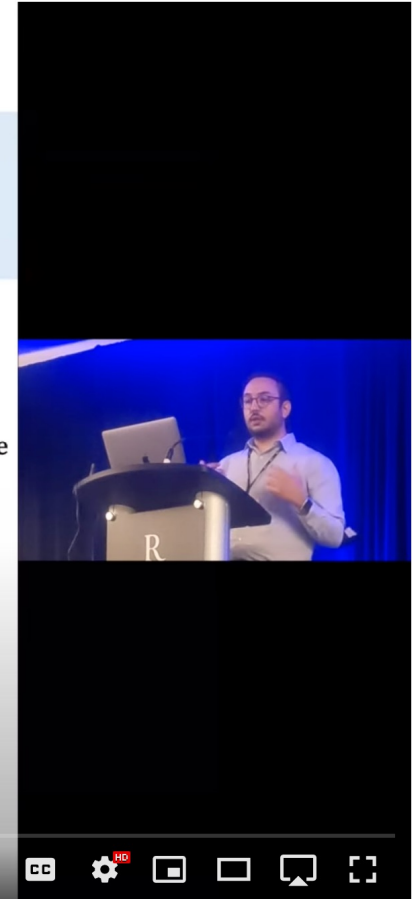
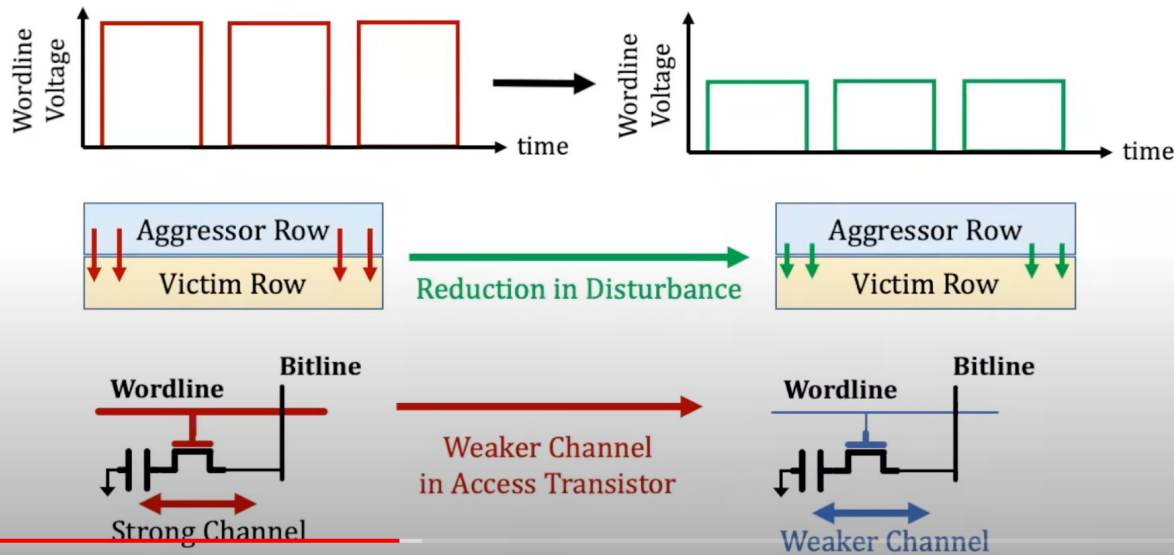
- **80%** of the tested DRAM chips **reliably operate using nominal refresh rate**
- Remaining **20%** **reliably operate** by
 - Using **single error correcting codes**
 - **Doubling the refresh rate** for **a small fraction (16.4%) of DRAM rows**

Reducing wordline voltage can **reduce RowHammer vulnerability**
without significantly affecting **reliable DRAM operation**

RowHammer vs. Wordline Voltage: Talk Video

Our Hypothesis

Reducing **wordline voltage**
can **reduce RowHammer vulnerability**
without significantly affecting **reliable DRAM operation**



Understanding RowHammer Under Reduced Wordline Voltage - Live Talk in DSN'22 by Giray Yaglikci



Onur Mutlu Lectures
30.2K subscribers



Subscribed

6



Share

Clip

Save



RowHammer in HBM Chips (2023)

- Ataberk Olgun, Majd Osserian, A. Giray Yağlıkçı, Yahya Can Tugrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez-Luna, and Onur Mutlu, **"An Experimental Analysis of RowHammer in HBM2 DRAM Chips"**
Proceedings of the 53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Disrupt Track (DSN Disrupt), Porto, Portugal, June 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (24 minutes, including Q&A)]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran^{1,2} A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami¹ Juan Gomez Luna¹ Onur Mutlu¹
¹SAFARI Research Group, ETH Zürich ²American University of Beirut

New RowHammer Solutions

TRRespass

Industry-Adopted Solutions Do Not Work

- Pietro Frigo, Emanuele Vannacci, Hasan Hassan, Victor van der Veen, Onur Mutlu, Cristiano Giuffrida, Herbert Bos, and Kaveh Razavi,
"TRRespass: Exploiting the Many Sides of Target Row Refresh"
Proceedings of the 41st IEEE Symposium on Security and Privacy (S&P), San Francisco, CA, USA, May 2020.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Lecture Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#)] (17 minutes)
[[Lecture Video](#)] (59 minutes)
[[Source Code](#)]
[[Web Article](#)]
Best Paper Award. IEEE Micro Top Pick Honorable Mention.
Pwnie Award 2020 for Most Innovative Research. [Pwnie Awards 2020](#)

TRRespass: Exploiting the Many Sides of Target Row Refresh

Pietro Frigo^{*†} Emanuele Vannacci^{*†} Hasan Hassan[§] Victor van der Veen[¶]
Onur Mutlu[§] Cristiano Giuffrida^{*} Herbert Bos^{*} Kaveh Razavi^{*}

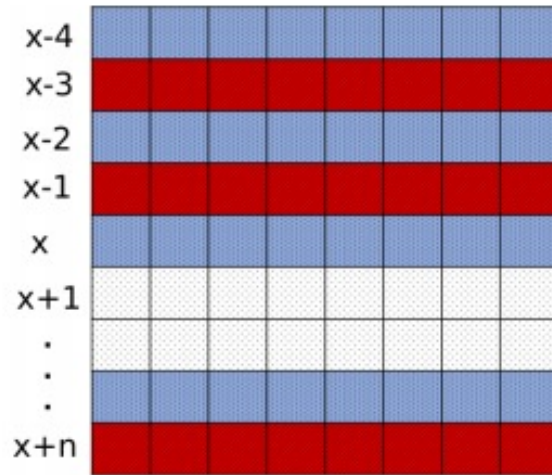
A Poor RowHammer Solution



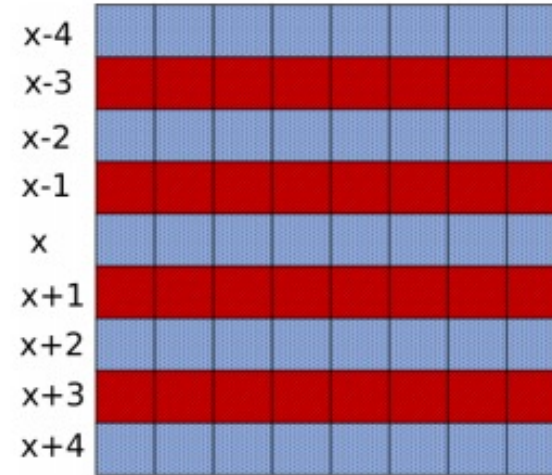
TRRespass

- First work to show that TRR-protected DRAM chips are vulnerable to RowHammer in the field
 - Mitigations advertised as secure are not secure
- Introduces the Many-sided RowHammer attack
 - Idea: Hammer many rows to bypass TRR mitigations (e.g., by overflowing proprietary TRR tables that detect aggressor rows)
- (Partially) reverse-engineers the TRR and pTRR mitigation mechanisms implemented in DRAM chips and memory controllers
- Provides an automatic tool that can effectively create many-sided RowHammer attacks in DDR4 and LPDDR4(X) chips

Example Many-Sided Hammering Patterns



(a) Assisted double-sided



(b) 4-sided

Fig. 12: Hammering patterns discovered by *TRRespass*. Aggressor rows are in red (■) and victim rows are in blue (■).

BitFlips vs. Number of Aggressor Rows

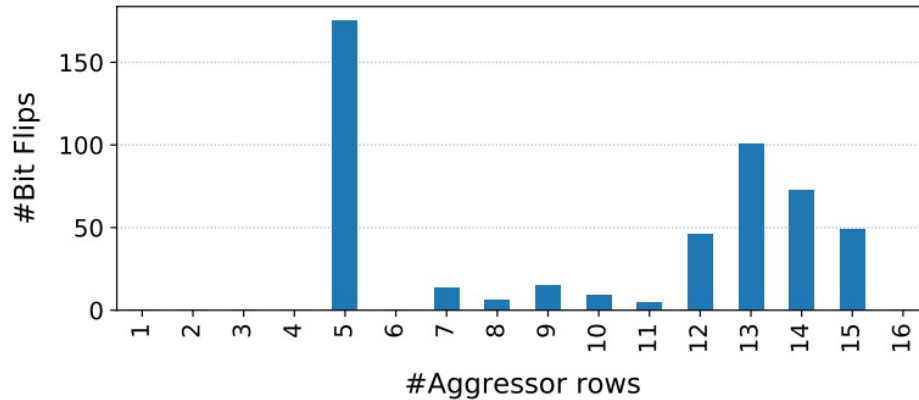


Fig. 10: Bit flips vs. number of aggressor rows. Module C_{12} : Number of bit flips in bank 0 as we vary the number of aggressor rows. Using SoftMC, we refresh DRAM with standard t_{REFI} and run the tests until each aggressor rows is hammered 500K times.

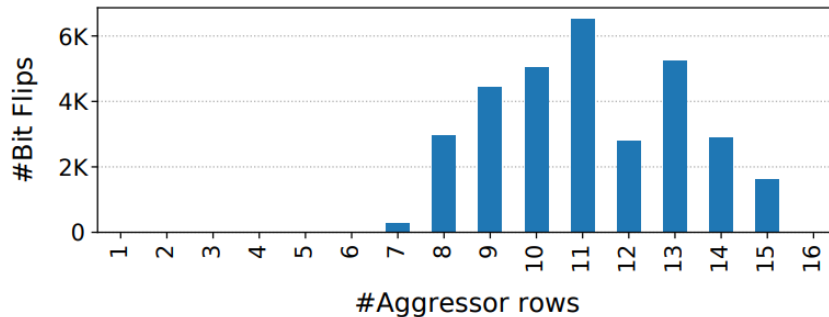


Fig. 11: Bit flips vs. number of aggressor rows. Module A_{15} : Number of bit flips in bank 0 as we vary the number of aggressor rows. Using SoftMC, we refresh DRAM with standard t_{REFI} and run the tests until each aggressor rows is hammered 500K times.

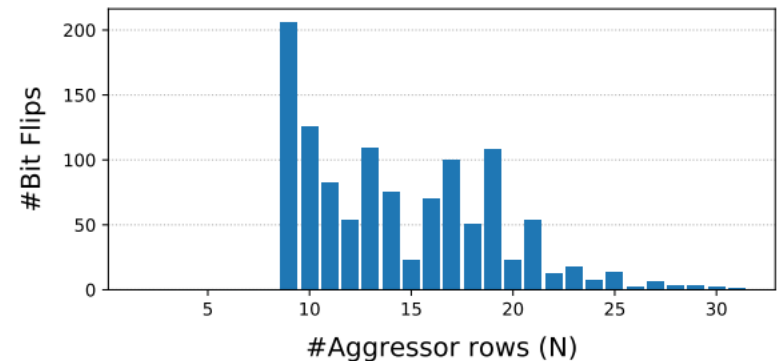


Fig. 13: Bit flips vs. number of aggressor rows. Module A_{10} : Number of bit flips triggered with N -sided RowHammer for varying number of N on Intel Core i7-7700K. Each aggressor row is one row away from the closest aggressor row (i.e., VAVAVA... configuration) and aggressor rows are hammered in a round-robin fashion.

TRRespass Vulnerable DRAM Modules

TABLE II: *TRRespass* results. We report the number of patterns found and bit flips detected for the 42 DRAM modules in our set.

| Module | Date (yy-ww) | Freq. (MHz) | Size (GB) | Organization | | | MAC | Found Patterns | Best Pattern | Corruptions | | | Double Refresh |
|-------------------------------|--------------------|----------------|--------------|--------------|-------|------|-----|-------------------|--------------|-------------|-------|--------|-------------------|
| | | | | Ranks | Banks | Pins | | | | Total | 1 → 0 | 0 → 1 | |
| $\mathcal{A}_{0,1,2,3}$ | 16-37 | 2132 | 4 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{A}_4 | 16-51 | 2132 | 4 | 1 | 16 | ×8 | UL | 4 | 9-sided | 7956 | 4008 | 3948 | — |
| \mathcal{A}_5 | 18-51 | 2400 | 4 | 1 | 8 | ×16 | UL | — | — | — | — | — | — |
| $\mathcal{A}_{6,7}$ | 18-15 | 2666 | 4 | 1 | 8 | ×16 | UL | — | — | — | — | — | — |
| \mathcal{A}_8 | 17-09 | 2400 | 8 | 1 | 16 | ×8 | UL | 33 | 19-sided | 20808 | 10289 | 10519 | — |
| \mathcal{A}_9 | 17-31 | 2400 | 8 | 1 | 16 | ×8 | UL | 33 | 19-sided | 24854 | 12580 | 12274 | — |
| \mathcal{A}_{10} | 19-02 | 2400 | 16 | 2 | 16 | ×8 | UL | 488 | 10-sided | 11342 | 1809 | 11533 | ✓ |
| \mathcal{A}_{11} | 19-02 | 2400 | 16 | 2 | 16 | ×8 | UL | 523 | 10-sided | 12830 | 1682 | 11148 | ✓ |
| $\mathcal{A}_{12,13}$ | 18-50 | 2666 | 8 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{A}_{14} | 19-08 [†] | 3200 | 16 | 2 | 16 | ×8 | UL | 120 | 14-sided | 32723 | 16490 | 16233 | — |
| $\mathcal{A}_{15}^{\ddagger}$ | 17-08 | 2132 | 4 | 1 | 16 | ×8 | UL | 2 | 9-sided | 22397 | 12351 | 10046 | — |
| \mathcal{B}_0 | 18-11 | 2666 | 16 | 2 | 16 | ×8 | UL | 2 | 3-sided | 17 | 10 | 7 | — |
| \mathcal{B}_1 | 18-11 | 2666 | 16 | 2 | 16 | ×8 | UL | 2 | 3-sided | 22 | 16 | 6 | — |
| \mathcal{B}_2 | 18-49 | 3000 | 16 | 2 | 16 | ×8 | UL | 2 | 3-sided | 5 | 2 | 3 | — |
| \mathcal{B}_3 | 19-08 [†] | 3000 | 8 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{B}_{4,5}$ | 19-08 [†] | 2666 | 8 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{B}_{6,7}$ | 19-08 [†] | 2400 | 4 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{B}_8^{\diamond} | 19-08 [†] | 2400 | 8 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{B}_9^{\diamond} | 19-08 [†] | 2400 | 8 | 1 | 16 | ×8 | UL | 2 | 3-sided | 12 | — | 12 | ✓ |
| $\mathcal{B}_{10,11}$ | 16-13 [†] | 2132 | 8 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{0,1}$ | 18-46 | 2666 | 16 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{2,3}$ | 19-08 [†] | 2800 | 4 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{4,5}$ | 19-08 [†] | 3000 | 8 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{6,7}$ | 19-08 [†] | 3000 | 16 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{C}_8 | 19-08 [†] | 3200 | 16 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| \mathcal{C}_9 | 18-47 | 2666 | 16 | 2 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{10,11}$ | 19-04 | 2933 | 8 | 1 | 16 | ×8 | UL | — | — | — | — | — | — |
| $\mathcal{C}_{12}^{\ddagger}$ | 15-01 [†] | 2132 | 4 | 1 | 16 | ×8 | UT | 25 | 10-sided | 190037 | 63904 | 126133 | ✓ |
| $\mathcal{C}_{13}^{\ddagger}$ | 18-49 | 2132 | 4 | 1 | 16 | ×8 | UT | 3 | 9-sided | 694 | 239 | 455 | — |

[†] The module does not report manufacturing date. Therefore, we report purchase date as an approximation.

[‡] Analyzed using the FPGA-based SoftMC.

[◊] The system runs with double refresh frequency in standard conditions. We configured the refresh interval to be 64 *ms* in the BIOS settings.

UL = Unlimited

UT = Untested

TRRespass Vulnerable Mobile Phones

TABLE III: LPDDR4(X) results. Mobile phones tested against *TRRespass* on ARMv8 sorted by production date. We found bit flip inducing RowHammer patterns on 5 out of 13mobile phones.

| <i>Mobile Phone</i> | <i>Year</i> | <i>SoC</i> | <i>Memory (GB)</i> | <i>Found Patterns</i> |
|-------------------------|-------------|-------------|--------------------|-----------------------|
| Google Pixel | 2016 | MSM8996 | 4 [†] | ✓ |
| Google Pixel 2 | 2017 | MSM8998 | 4 | — |
| Samsung G960F/DS | 2018 | Exynos 9810 | 4 | — |
| Huawei P20 DS | 2018 | Kirin 970 | 4 | — |
| Sony XZ3 | 2018 | SDM845 | 4 | — |
| HTC U12+ | 2018 | SDM845 | 6 | — |
| LG G7 ThinQ | 2018 | SDM845 | 4 [†] | ✓ |
| Google Pixel 3 | 2018 | SDM845 | 4 | ✓ |
| Google Pixel 4 | 2019 | SM8150 | 6 | — |
| OnePlus 7 | 2019 | SM8150 | 8 | ✓ |
| Samsung G970F/DS | 2019 | Exynos 9820 | 6 | ✓ |
| Huawei P30 DS | 2019 | Kirin 980 | 6 | — |
| Xiaomi Redmi Note 8 Pro | 2019 | Helio G90T | 6 | — |

[†] LPDDR4 (not LPDDR4X)

TRRespass Based RowHammer Attack

TABLE IV: Time to exploit. Time to find the first exploitable template on two sample modules from each DRAM vendor.

| <i>Module</i> | τ (<i>ms</i>) | <i>PTE</i> [81] | <i>RSA-2048</i> [79] | <i>sudo</i> [27] |
|--------------------|----------------------|-----------------|----------------------|------------------|
| \mathcal{A}_{14} | 188.7 | 4.9s | 6m 27s | — |
| \mathcal{A}_4 | 180.8 | 38.8s | 39m 28s | — |
| \mathcal{B}_1 | 360.7 | — | — | — |
| \mathcal{B}_2 | 331.2 | — | — | — |
| \mathcal{C}_{12} | 300.0 | 2.3s | 74.6s | 54m16s |
| \mathcal{C}_{13} | 180.9 | 3h 15m | — | — |

τ : Time to template a single row: time to fill the victim and aggressor rows + hammer time + time to scan the row.

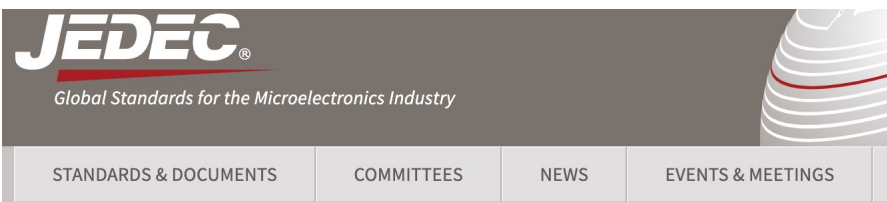
TRRespass Key Results

- 13 out of 42 tested DDR4 DRAM modules are vulnerable
 - From all 3 major manufacturers
 - 3-, 9-, 10-, 14-, 19-sided hammer attacks needed
- 5 out of 13 mobile phones tested vulnerable
 - From 4 major manufacturers
 - With LPDDR4(X) DRAM chips
- These results are scratching the surface
 - TRRespass tool is not exhaustive
 - There is a lot of room for uncovering more vulnerable chips and phones

RowHammer is still
an open problem

Security by obscurity
is likely not a good solution

Improvements in JEDEC (2020-2021)



NEAR-TERM DRAM LEVEL ROWHAMMER MITIGATION

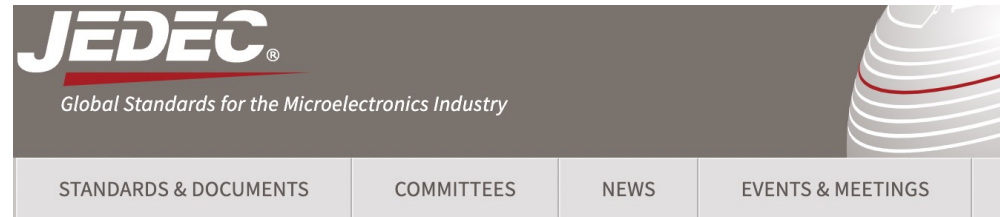
JEP300-1

Published: Mar 2021

RAM process node transistor scaling for power and DRAM capacity has made DRAM cells more sensitive to disturbances or transient faults. This sensitivity becomes much worse if external stresses are applied in a meticulously manipulated sequence, such as Rowhammer. Rowhammer related papers have been written outside of JEDEC, but some assumptions used in those papers didn't explain the problem very clearly or correctly, so the perception for this matter is not precisely understood within the industry. This publication defines the problem and recommends following mitigations to address such concerns across the DRAM industry or academia. Item 1866.01.

Committee(s): [JC-42](#)

<https://www.jedec.org/standards-documents/docs/jep300-1>



SYSTEM LEVEL ROWHAMMER MITIGATION

JEP301-1

Published: Mar 2021

A DRAM rowhammer security exploit is a serious threat to cloud service providers, data centers, laptops, smart phones, self-driving cars and IoT devices. Hardware research and development will take time. DRAM components, DRAM DIMMs, System-on-chip (SoC), chipsets and system products have their own design cycle time and overall life time. This publication recommends best practices to mitigate the security risks from rowhammer attacks. Item 1866.02.

Committee(s): [JC-42](#)

<https://www.jedec.org/standards-documents/docs/jep301-1>

Uncovering TRR Almost Completely

Industry-Adopted Solutions Are Very Poor

- Hasan Hassan, Yahya Can Tugrul, Jeremie S. Kim, Victor van der Veen, Kaveh Razavi, and Onur Mutlu,
"Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications"
Proceedings of the 54th International Symposium on Microarchitecture (MICRO), Virtual, October 2021.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Short Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Lightning Talk Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (25 minutes)]
[[Lightning Talk Video](#) (100 seconds)]
[[arXiv version](#)]

Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications

Hasan Hassan[†]

[†]ETH Zürich

Yahya Can Tuğrul^{†‡}

Kaveh Razavi[†]
[‡]TOBB University of Economics & Technology

Jeremie S. Kim[†]

Onur Mutlu[†]

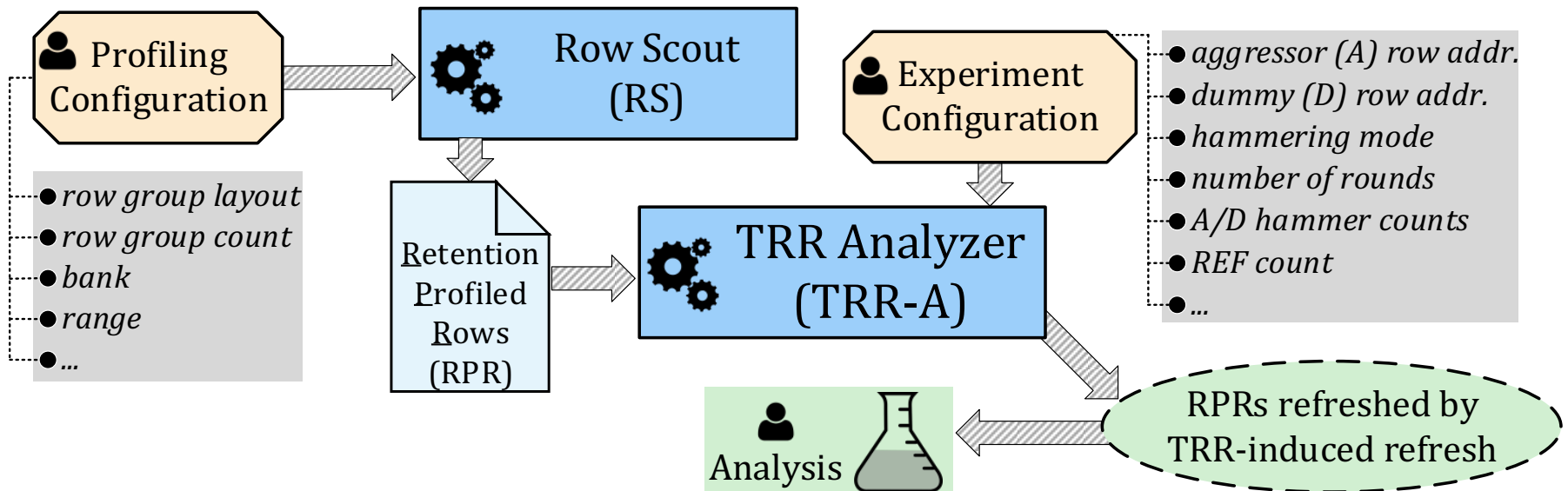
Victor van der Veen^σ

^σQualcomm Technologies Inc.

Overview of U-TRR

U-TRR: A new methodology to *uncover* the inner workings of TRR

Key idea: Use **data retention failures** as a side channel to **detect when a row is refreshed** by TRR



Key Takeaways

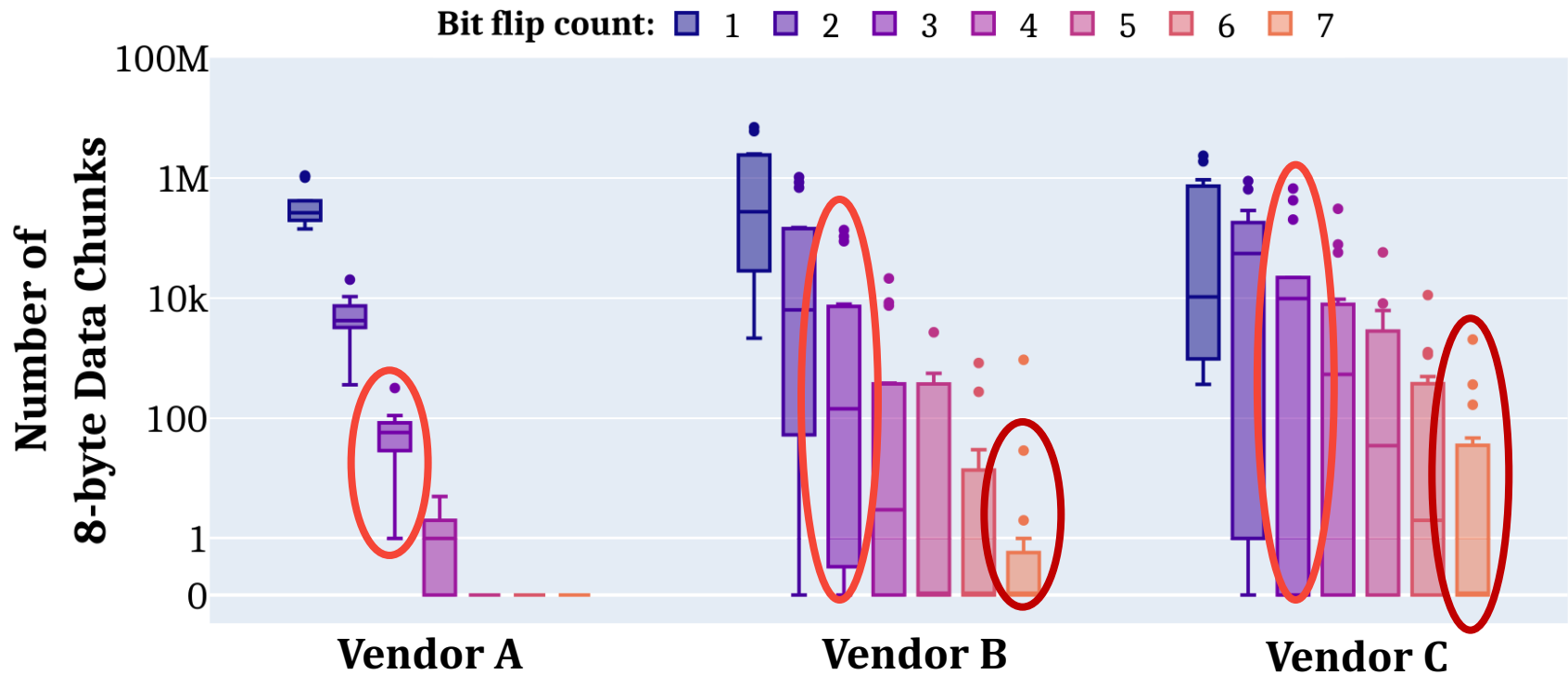
All 45 modules we test are vulnerable

99.9% of rows in a DRAM bank
experience **at least one RowHammer bit flip**

ECC is ineffective: up to **7 RowHammer bit flips**
in an 8-byte dataword

| Module | Date (yy-ww) | Chip Density (Gbit) | Organization | | | HC_{first}^{\dagger} | Our Key TRR Observations and Results | | | | | | | |
|--------|-----------------|---------------------------|--------------|-------|------|------------------------|--------------------------------------|------------------------|-----------------------|-----------------|---------------------|------------------------|--|---|
| | | | Ranks | Banks | Pins | | Version | Aggressor Detection | Aggressor Capacity | Per-Bank TRR | TRR-to-REF Ratio | Neighbors Refreshed | % Vulnerable DRAM Rows [†] | Max. Bit Flips per Row per Hammer [†] |
| A0 | 19-50 | 8 | 1 | 16 | 8 | 16K | A_{TRR1} | Counter-based | 16 | ✓ | 1/9 | 4 | 73.3% | 1.16 |
| A1-5 | 19-36 | 8 | 1 | 8 | 16 | 13K-15K | A_{TRR1} | Counter-based | 16 | ✓ | 1/9 | 4 | 99.2% - 99.4% | 2.32 - 4.73 |
| A6-7 | 19-45 | 8 | 1 | 8 | 16 | 13K-15K | A_{TRR1} | Counter-based | 16 | ✓ | 1/9 | 4 | 99.3% - 99.4% | 2.12 - 3.86 |
| A8-9 | 20-07 | 8 | 1 | 16 | 8 | 12K-14K | A_{TRR1} | Counter-based | 16 | ✓ | 1/9 | 4 | 74.6% - 75.0% | 1.96 - 2.96 |
| A10-12 | 19-51 | 8 | 1 | 16 | 8 | 12K-13K | A_{TRR1} | Counter-based | 16 | ✓ | 1/9 | 4 | 74.6% - 75.0% | 1.48 - 2.86 |
| A13-14 | 20-31 | 8 | 1 | 8 | 16 | 11K-14K | A_{TRR2} | Counter-based | 16 | ✓ | 1/9 | 2 | 94.3% - 98.6% | 1.53 - 2.78 |
| B0 | 18-22 | 4 | 1 | 16 | 8 | 44K | B_{TRR1} | Sampling-based | 1 | ✗ | 1/4 | 2 | 99.9% | 2.13 |
| B1-4 | 20-17 | 4 | 1 | 16 | 8 | 159K-192K | B_{TRR1} | Sampling-based | 1 | ✗ | 1/4 | 2 | 23.3% - 51.2% | 0.06 - 0.11 |
| B5-6 | 16-48 | 4 | 1 | 16 | 8 | 44K-50K | B_{TRR1} | Sampling-based | 1 | ✗ | 1/4 | 2 | 99.9% | 1.85 - 2.03 |
| B7 | 19-06 | 8 | 2 | 16 | 8 | 20K | B_{TRR1} | Sampling-based | 1 | ✗ | 1/4 | 2 | 99.9% | 31.14 |
| B8 | 18-03 | 4 | 1 | 16 | 8 | 43K | B_{TRR1} | Sampling-based | 1 | ✗ | 1/4 | 2 | 99.9% | 2.57 |
| B9-12 | 19-48 | 8 | 1 | 16 | 8 | 42K-65K | B_{TRR2} | Sampling-based | 1 | ✗ | 1/9 | 2 | 36.3% - 38.9% | 16.83 - 24.26 |
| B13-14 | 20-08 | 4 | 1 | 16 | 8 | 11K-14K | B_{TRR3} | Sampling-based | 1 | ✓ | 1/2 | 4 | 99.9% | 16.20 - 18.12 |
| C0-3 | 16-48 | 4 | 1 | 16 | x8 | 137K-194K | C_{TRR1} | Mix | Unknown | ✓ | 1/17 | 2 | 1.0% - 23.2% | 0.05 - 0.15 |
| C4-6 | 17-12 | 8 | 1 | 16 | x8 | 130K-150K | C_{TRR1} | Mix | Unknown | ✓ | 1/17 | 2 | 7.8% - 12.0% | 0.06 - 0.08 |
| C7-8 | 20-31 | 8 | 1 | 8 | x16 | 40K-44K | C_{TRR1} | Mix | Unknown | ✓ | 1/17 | 2 | 39.8% - 41.8% | 9.66 - 14.56 |
| C9-11 | 20-31 | 8 | 1 | 8 | x16 | 42K-53K | C_{TRR2} | Mix | Unknown | ✓ | 1/9 | 2 | 99.7% | 9.30 - 32.04 |
| C12-14 | 20-46 | 16 | 1 | 8 | x16 | 6K-7K | C_{TRR3} | Mix | Unknown | ✓ | 1/8 | 2 | 99.9% | 4.91 - 12.64 |

Bypassing ECC with New RowHammer Patterns



Modules from all three vendors have many **8-byte data chunks** with **3 and more (up to 7) RowHammer bit flips**

Conventional DRAM ECC **cannot protect** against our **new RowHammer access patterns**

Google's Half-Double RowHammer Attack (May 2021)

Google Security Blog

The latest news and insights from Google on security and safety on the Internet

Introducing Half-Double: New hammering technique for DRAM Rowhammer bug

May 25, 2021

Research Team: Salman Qazi, Yoongu Kim, Nicolas Boichat, Eric Shiu & Mattias Nissler

Today, we are sharing details around our discovery of [Half-Double](#), a new Rowhammer technique that capitalizes on the worsening physics of some of the newer DRAM chips to alter the contents of memory.

Rowhammer is a DRAM vulnerability whereby repeated accesses to one address can tamper with the data stored at other addresses. Much like speculative execution vulnerabilities in CPUs, Rowhammer is a breach of the security guarantees made by the underlying hardware. As an electrical coupling phenomenon within the silicon itself, Rowhammer allows the potential bypass of hardware and software memory protection policies. This can allow untrusted code to break out of its sandbox and take full control of the system.

Google's Half-Double RowHammer Attack (May 2021)



- Given three consecutive rows A, B, and C, we were able to attack C by directing a very large number of accesses to A, along with just a handful (~dozens) to B.
- Based on our experiments, accesses to B have a non-linear gating effect, in which they appear to “transport” the Rowhammer effect of A onto C.
- This is likely an indication that the electrical coupling responsible for **Rowhammer** is a property of distance, **effectively becoming stronger** and longer-ranged as cell geometries shrink down.

Google's Half-Double RowHammer Attack

■ Appears at USENIX Security 2022

Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

¹*Graz University of Technology* ²*Lamarr Security Research* ³*Google*
⁴*Amazon Web Services* ⁵*Rivos*

BlockHammer Solution in 2021

- A. Giray Yaglikci, Minesh Patel, Jeremie S. Kim, Roknoddin Azizi, Ataberk Olgun, Lois Orosa, Hasan Hassan, Jisung Park, Konstantinos Kanellopoulos, Taha Shahroodi, Saugata Ghose, and Onur Mutlu,

"BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows"

Proceedings of the 27th International Symposium on High-Performance Computer Architecture (HPCA), Virtual, February-March 2021.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Intel Hardware Security Academic Awards Short Talk Slides \(pptx\)](#) ([pdf](#))]

[[Talk Video](#) (22 minutes)]

[[Short Talk Video](#) (7 minutes)]

[[Intel Hardware Security Academic Awards Short Talk Video](#) (2 minutes)]

[[BlockHammer Source Code](#)]

Intel Hardware Security Academic Award Finalist (one of 4 finalists out of 34 nominations)

BlockHammer: Preventing RowHammer at Low Cost by Blacklisting Rapidly-Accessed DRAM Rows

A. Giray Yağlıkçı¹ Minesh Patel¹ Jeremie S. Kim¹ Roknoddin Azizi¹ Ataberk Olgun¹ Lois Orosa¹
Hasan Hassan¹ Jisung Park¹ Konstantinos Kanellopoulos¹ Taha Shahroodi¹ Saugata Ghose² Onur Mutlu¹

¹ETH Zürich

²University of Illinois at Urbana-Champaign

Two Key Challenges

1

Scalability

with worsening RowHammer vulnerability

2

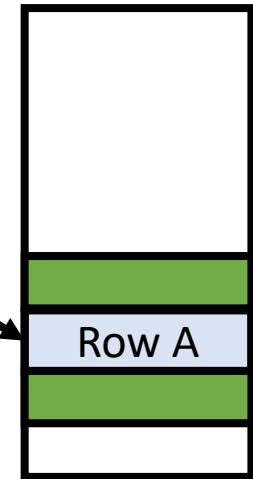
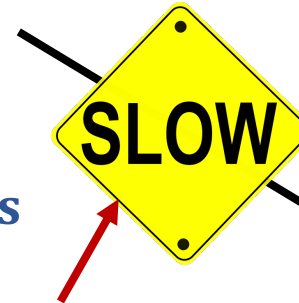
Compatibility

with commodity DRAM chips

BlockHammer: Practical Throttling-based Mechanism



- A RowHammer attack hammers Row A
- **BlockHammer** detects a RowHammer attack using **area-efficient Bloom filters**
- **BlockHammer** **selectively throttles accesses** from within **the memory controller**
- Bit flips **do not** occur
- BlockHammer can *optionally* **inform the system software** about the attack



Physical
Row Layout

BlockHammer is compatible with commodity DRAM chips
No need for proprietary info of or modifications to DRAM chips

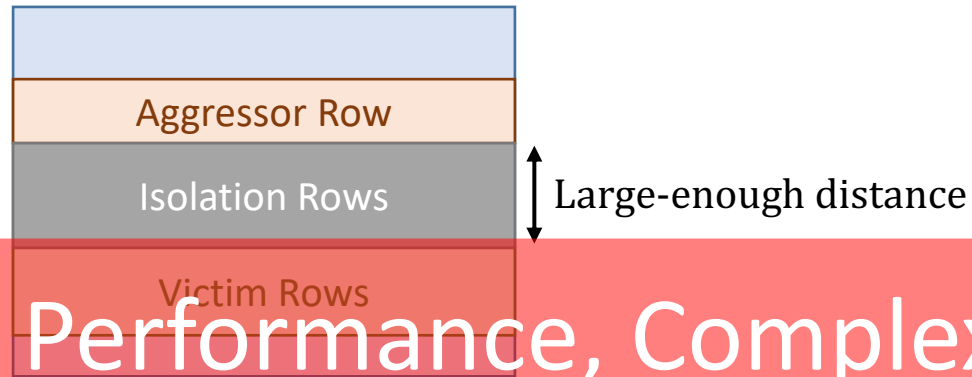
Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

RowHammer Solution Approaches

- More robust DRAM chips **and/or** error-correcting codes
- Increased refresh rate

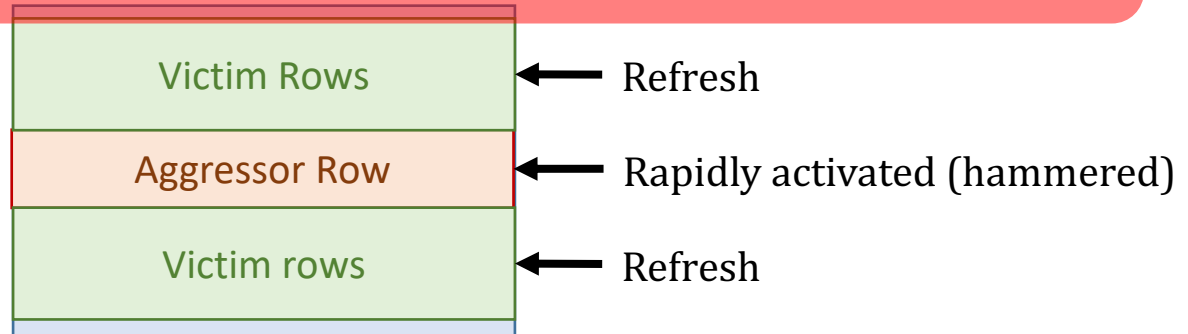


- Physical isolation



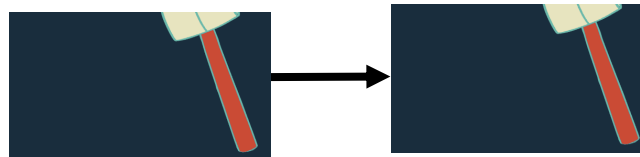
Cost, Power, Performance, Complexity

- Reactive refresh



- Proactive throttling

SAFARI



Fewer activations allowed for aggressive applications

RowHammer in 2023: SK Hynix

ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyong Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

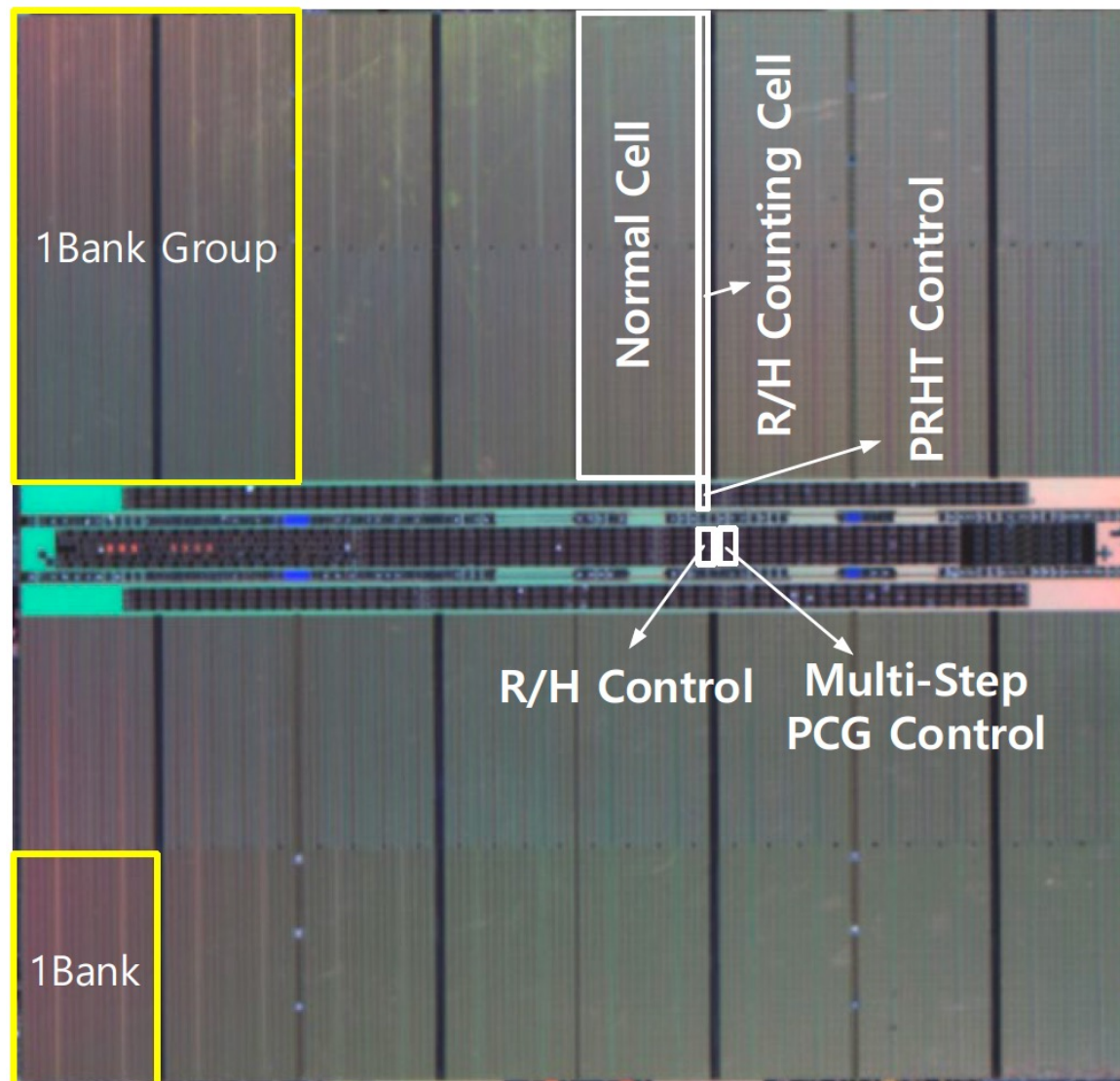


Industry's RowHammer Solutions (I)

SK hynix Semiconductor, Icheon, Korea

DRAM products have been recently adopted in a wide range of high-performance computing applications: such as in cloud computing, in big data systems, and IoT devices. This demand creates larger memory capacity requirements, thereby requiring aggressive DRAM technology node scaling to reduce the cost per bit [1,2]. However, DRAM manufacturers are facing technology scaling challenges due to row hammer and refresh retention time beyond 1a-nm [2]. Row hammer is a failure mechanism, where repeatedly activating a DRAM row disturbs data in adjacent rows. Scaling down severely threatens reliability since a reduction of DRAM cell size leads to a reduction in the intrinsic row hammer tolerance [2,3]. To improve row hammer tolerance, there is a need to probabilistically activate adjacent rows with carefully sampled active addresses and to improve intrinsic row hammer tolerance [2]. In this paper, row-hammer-protection and refresh-management schemes are presented to guarantee DRAM security and reliability despite the aggressive scaling from 1a-nm to sub 10-nm nodes. The probabilistic-aggressor-tracking scheme with a refresh-management function (RFM) and per-row hammer tracking (PRHT) improve DRAM resilience. A multi-step precharge reinforces intrinsic row-hammer tolerance and a core-bias modulation improves retention time: even in the face of cell-transistor degradation due to technology scaling. This comprehensive scheme leads to a reduced probability of failure, due to row hammer attacks, by 93.1% and an improvement in retention time by 17%.

Industry's RowHammer Solutions (II)



ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyoung Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

RowHammer in 2023: Samsung

DSAC: Low-Cost Rowhammer Mitigation Using In-DRAM Stochastic and Approximate Counting Algorithm

Seungki Hong Dongha Kim Jaehyung Lee Reum Oh
Changsik Yoo Sangjoon Hwang Jooyoung Lee

DRAM Design Team, Memory Division, Samsung Electronics

<https://arxiv.org/pdf/2302.03591v1.pdf>

Panopticon: A Complete In-DRAM Rowhammer Mitigation

Tanj Bennett[§], Stefan Saroiu, Alec Wolman, and Lucian Cojocar
Microsoft, [§]Avant-Gray LLC

<https://stefan.t8k2.com/publications/dramsec/2021/panopticon.pdf>

Are we now
RowHammer-free
in 2023 and Beyond?

Are We Now RowHammer Free in 2023?

- **Appeared at ISCA in June 2023**

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu
ETH Zürich

<https://arxiv.org/pdf/2306.17061.pdf>

RowPress



- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu, **"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**

Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Video](#) (3 minutes)]

[[RowPress Source Code and Datasets \(Officially Artifact Evaluated with All Badges\)](#)]

***Officially artifact evaluated as available, reusable and reproducible.
Best artifact award at ISCA 2023. IEEE Micro Top Pick in 2024.***

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu

ETH Zürich



RowPress

Amplifying Read Disturbance in Modern DRAM Chips

ISCA 2023 Session 2B: Monday 19 June, 2:15 PM EDT

Haocong Luo

Ataberk Olgun

A. Giray Yağlıkçı

Yahya Can Tuğrul

Steve Rhyner

Meryem Banu Cavlak

Joël Lindegger

Mohammad Sadrosadati

Onur Mutlu

SAFARI

ETH zürich

High-Level Summary

- We demonstrate and analyze **RowPress, a new read disturbance phenomenon** that causes bitflips in real DRAM chips
- We show that RowPress is **different from the RowHammer vulnerability**
- We demonstrate RowPress **using a user-level program** on a real Intel system with real DRAM chips
- We provide **effective solutions** to RowPress

What is RowPress?

Keeping a DRAM row **open for a long time** causes bitflips in adjacent rows

These bitflips do **NOT** require many row activations

Only one activation is enough in some cases!



Now, let's delve into some background and see how this is **different from RowHammer**

Are There Other Read-Disturb Issues in DRAM?

- RowHammer is the only studied read-disturb phenomenon
- Mitigations work by detecting **high row activation count**

What if there is another read-disturb phenomenon that **does NOT rely on high row activation count**?



https://www.reddit.com/r/CrappyDesign/comments/arw0q8/now_this_this_is_poor_fencing/

RowPress vs. RowHammer

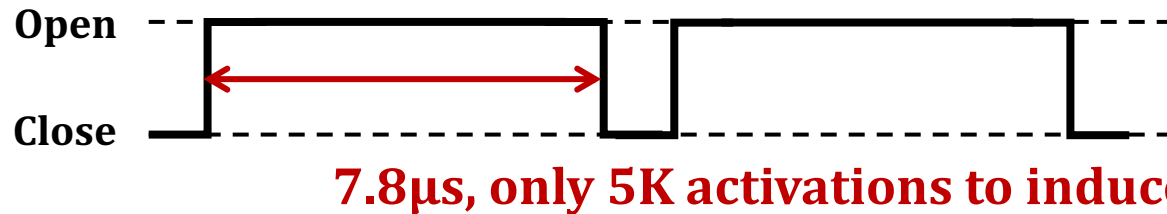
Instead of using a high activation count,

☞ increase the time that the aggressor row stays open

RowHammer
Aggressor Row



RowPress
Aggressor Row

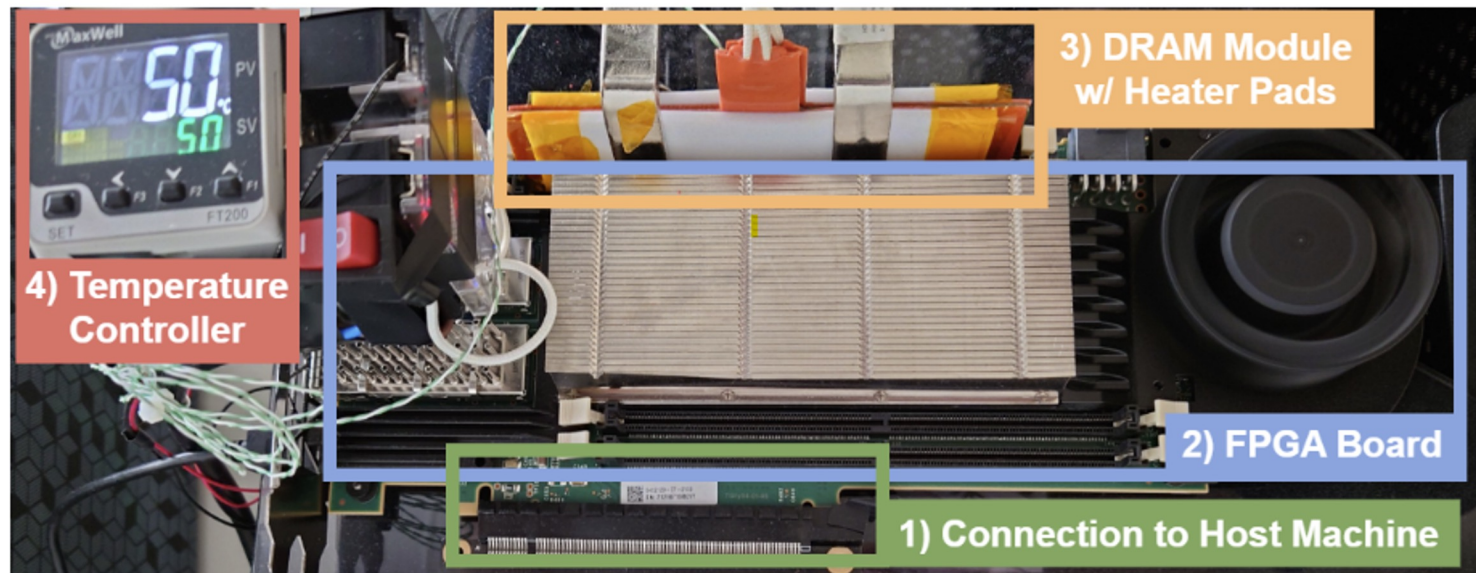


We observe bitflips even with **ONLY ONE activation** in extreme cases where the row stays open for 30ms

Real DRAM Chip Characterization (I)

FPGA-Based DDR4 Testing Infrastructure

- Based on [SoftMC \[Hassan+, HPCA'17\]](#) and [DRAM Bender \[Olgun+, TCAD'23\]](#)
- **Fine-grained control** over DRAM commands, timings, and temperature



Real DRAM Chip Characterization (II)

DRAM chips tested

- 164 DDR4 chips from all 3 major DRAM manufacturers
- Covers different die densities and revisions

| Mfr. | #DIMMs | #Chips | Density | Die Rev. | Org. | Date |
|----------------------|--------|--------|---------|----------|------|-------|
| Mfr. S (Samsung) | 2 | 8 | 8Gb | B | x8 | 20-53 |
| | 1 | 8 | 8Gb | C | x8 | N/A |
| | 3 | 8 | 8Gb | D | x8 | 21-10 |
| | 2 | 8 | 4Gb | F | x8 | N/A |
| Mfr. H (SK Hynix) | 1 | 8 | 4Gb | A | x8 | 19-46 |
| | 1 | 8 | 4Gb | X | x8 | N/A |
| | 2 | 8 | 16Gb | A | x8 | 20-51 |
| | 2 | 8 | 16Gb | C | x8 | 21-36 |
| Mfr. M (Micron) | 1 | 16 | 8Gb | B | x4 | N/A |
| | 2 | 4 | 16Gb | B | x16 | 21-26 |
| | 1 | 16 | 16Gb | E | x4 | 20-14 |
| | 2 | 4 | 16Gb | E | x16 | 20-46 |
| | 1 | 4 | 16Gb | F | x16 | 21-50 |

Major Takeaways from Real DRAM Chips

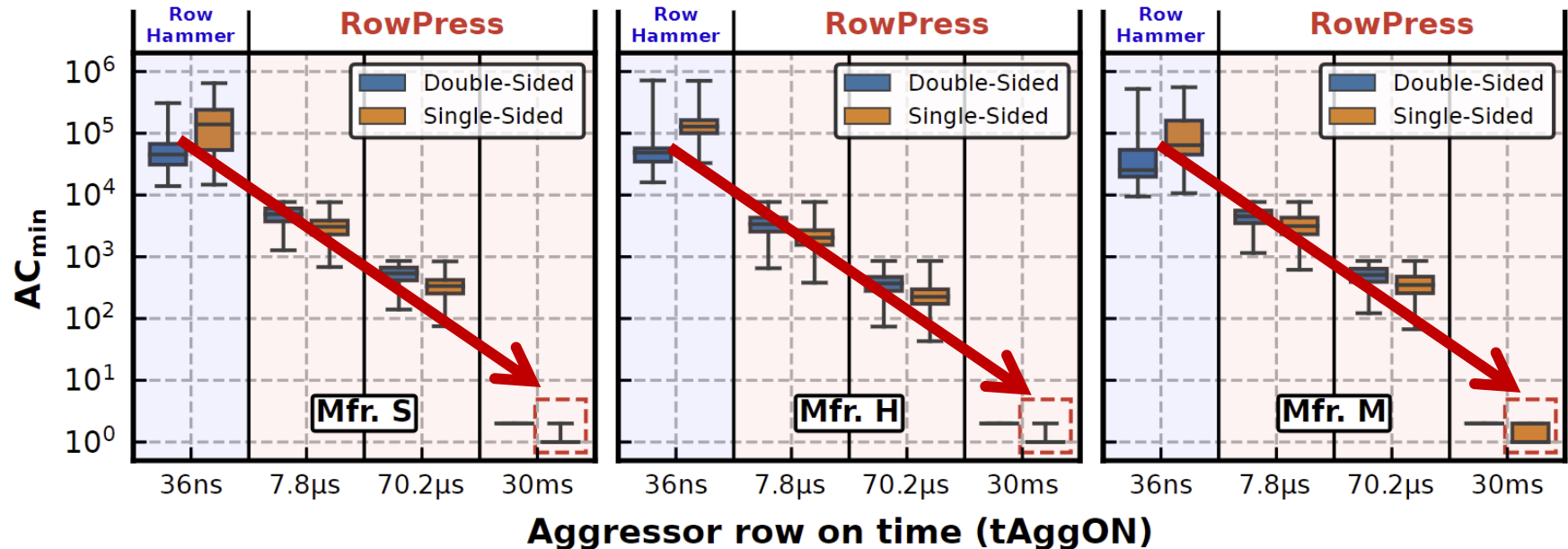
RowPress significantly **amplifies** DRAM's vulnerability to **read disturbance**

RowPress has a **different** underlying error **mechanism** from RowHammer

Key Characteristics of RowPress (I)

Amplifying Read Disturbance in DRAM

- Reduces the minimum number of row activations needed to induce a bitflip (AC_{min}) by **1-2 orders of magnitude**
- In extreme cases, activating a row **only once** induces bitflips



Key Characteristics of RowPress (II)

Amplifying Read Disturbance in DRAM

- Reduces the minimum number of row activations needed to induce a bitflip (AC_{min}) by **1-2 orders of magnitude**
- In extreme cases, activating a row **only once** induces bitflips
- Gets worse as **temperature increases**

Different From RowHammer

- Affects a **different set of cells** compared to RowHammer and retention failures
- **Behaves differently** as access pattern and temperature changes compared to RowHammer

Real-System Demonstration (I)



Intel Core i5-10400
(Comet Lake)



Samsung DDR4 Module
M378A2K43CB1-CTD
(Date Code: 20-10)
w/ TRR RowHammer Mitigation

Key Idea: A proof-of-concept RowPress program keeps a DRAM row open for a longer period by **keeping on accessing different cache blocks in the row**

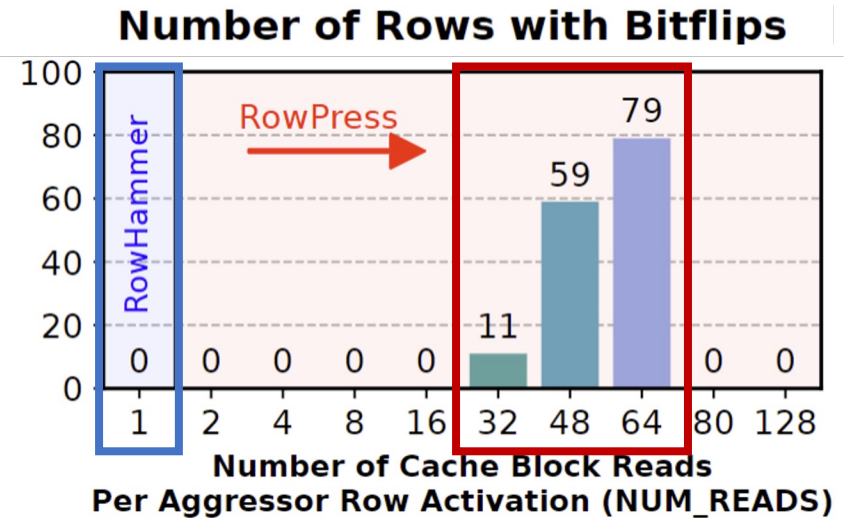
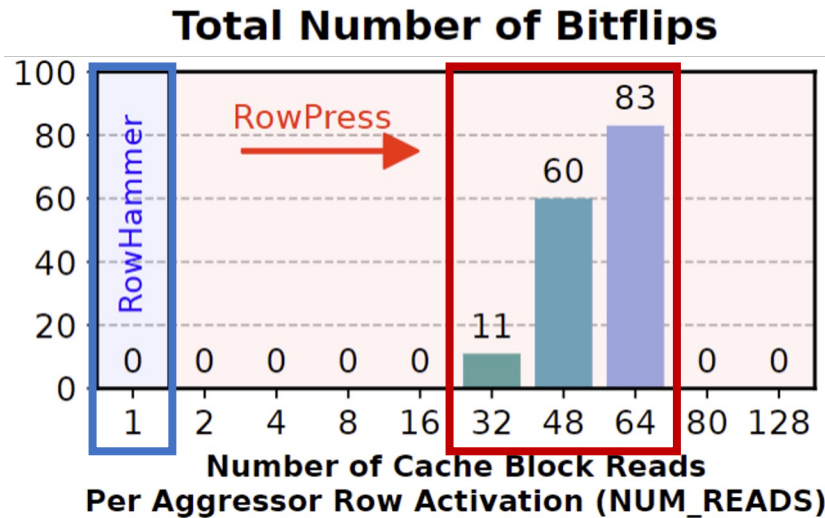
```
// Sync with Refresh and Loop Below
```

```
for (k = 0; k < NUM_AGGR_ACTS; k++)  
    for (j = 0; j < NUM_READS; j++) *AGGRESSOR1[j];  
    for (j = 0; j < NUM_READS; j++) *AGGRESSOR2[j];  
    for (j = 0; j < NUM_READS; j++)  
        clflushopt(AGGRESSOR1[j]);  
        clflushopt(AGGRESSOR2[j]);  
    mfence();  
    activate_dummy_rows();
```

**Number of Cache Blocks Accessed
Per Aggressor Row ACT
(NUM_READS=1 is Rowhammer)**

Real-System Demonstration (II)

On 1500 victim rows



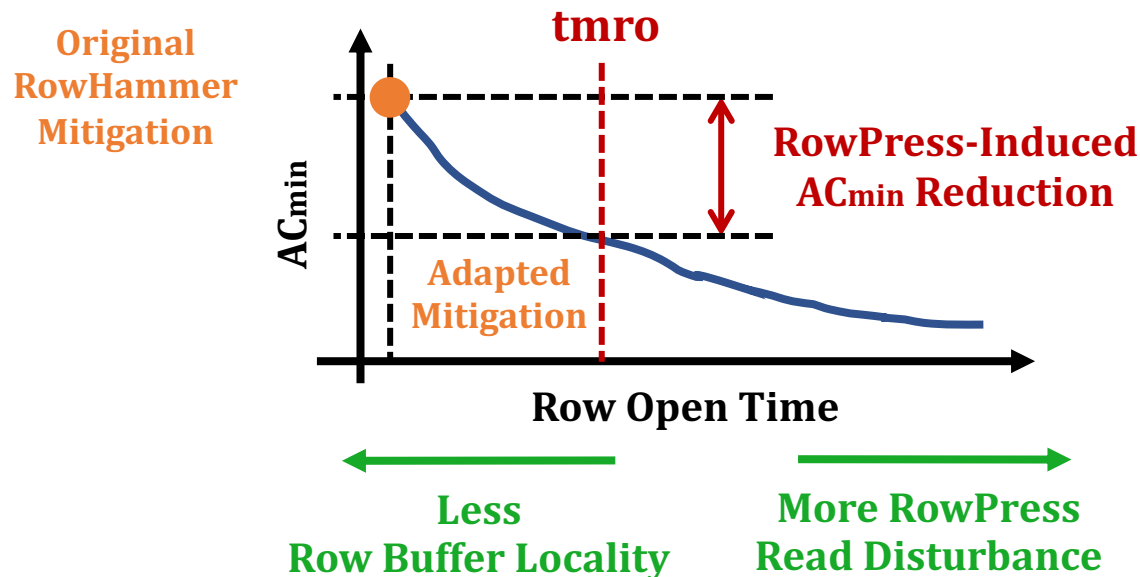
Leveraging RowPress, our user-level program induces bitflips when RowHammer cannot

Mitigating RowPress (I)

We propose a methodology to adapt existing RowHammer mitigations to **also mitigate RowPress**

Key Idea:

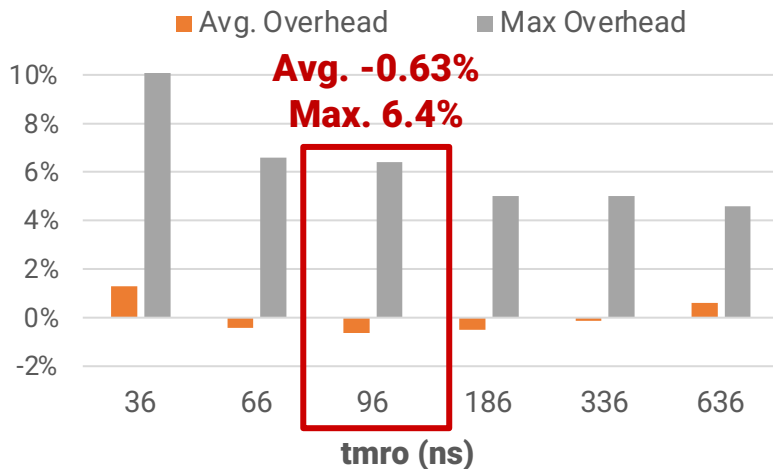
1. Limit the maximum row open time (**tmro**)
2. Configure the RowHammer mitigation to account for the **RowPress-induced reduction in ACmin**



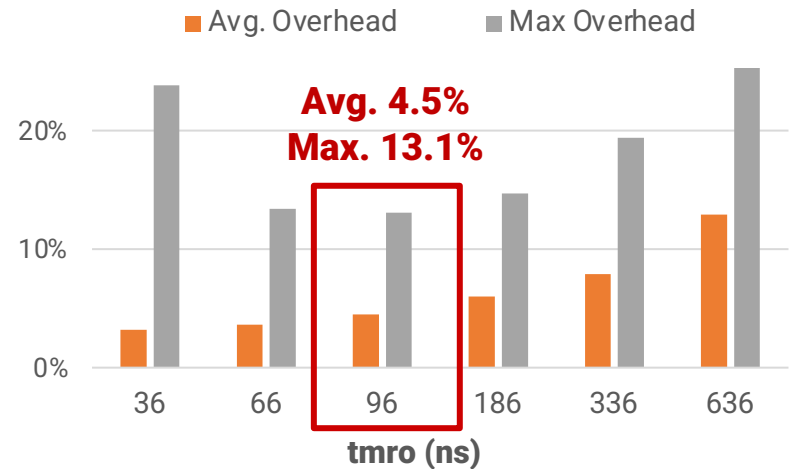
Mitigating RowPress (II)

Key evaluation results

Additional Performance Overhead of Graphene-RP



Additional Performance Overhead of PARA-RP



**Our solutions mitigate RowPress
at low additional performance overhead**

More Results & Source Code

Many more results & analyses in the paper

- 6 major takeaways
- 19 major empirical observations
- 3 more potential mitigations



Fully open source and artifact evaluated

- <https://github.com/CMU-SAFARI/RowPress>





- Haocong Luo, Ataberk Olgun, Giray Yaglikci, Yahya Can Tugrul, Steve Rhyner, M. Banu Cavlak, Joel Lindegger, Mohammad Sadrosadati, and Onur Mutlu, **"RowPress: Amplifying Read Disturbance in Modern DRAM Chips"**

Proceedings of the 50th International Symposium on Computer Architecture (ISCA), Orlando, FL, USA, June 2023.

[[Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Slides \(pptx\)](#) ([pdf](#))]

[[Lightning Talk Video](#) (3 minutes)]

[[RowPress Source Code and Datasets \(Officially Artifact Evaluated with All Badges\)](#)]

***Officially artifact evaluated as available, reusable and reproducible.
Best artifact award at ISCA 2023. IEEE Micro Top Pick in 2024.***

RowPress: Amplifying Read-Disturbance in Modern DRAM Chips

Haocong Luo Ataberk Olgun A. Giray Yağlıkçı Yahya Can Tuğrul Steve Rhyner
Meryem Banu Cavlak Joël Lindegger Mohammad Sadrosadati Onur Mutlu

ETH Zürich

More to Come...

Two Major Directions

- **Understanding Bitflips (Hardware errors in general)**
 - Many effects on bitflips still need to be rigorously examined
 - Aging of DRAM Chips
 - Environmental Conditions (e.g., Process, Voltage, Temperature)
 - Memory Access Patterns
 - Memory Controller & System Design Decisions
 - ...

- **Solving Bitflips (Hardware errors in general)**
 - Flexible and efficient solutions are necessary
 - In-field patchable / reconfigurable / programmable solutions
 - Co-architecting across the system stack/components is important
 - To avoid performance and denial-of-service problems

A RowHammer Survey: Recent Update

- Onur Mutlu, Ataberk Olgun, and A. Giray Yaglikci,
"Fundamentally Understanding and Solving RowHammer"
Invited Special Session Paper at the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Tokyo, Japan, January 2023.
[arXiv version]
[Slides (pptx) (pdf)]
[Talk Video (26 minutes)]

Fundamentally Understanding and Solving RowHammer

Onur Mutlu
onur.mutlu@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

Ataberk Olgun
ataberk.olgund@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

A. Giray Yağlıkçı
giray.yaglikci@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

<https://arxiv.org/pdf/2211.07613.pdf>

A Case for Transparent Reliability in DRAM Systems

Minesh Patel[†] Taha Shahroodi^{‡†} Aditya Manglik[†] A. Giray Yağlıkçı[†]
Ataberk Olgun[†] Haocong Luo[†] Onur Mutlu[†]

[†]*ETH Zürich* [‡]*TU Delft*

<https://arxiv.org/pdf/2204.10378.pdf>

Better Partitioning of DRAM & Controller

A Case for Self-Managing DRAM Chips: Improving Performance, Efficiency, Reliability, and Security via Autonomous in-DRAM Maintenance Operations

Hasan Hassan

Ataberk Olgun

A. Giray Yağlıkçı

Haocong Luo

Onur Mutlu

ETH Zürich

<https://arxiv.org/pdf/2207.13358.pdf>

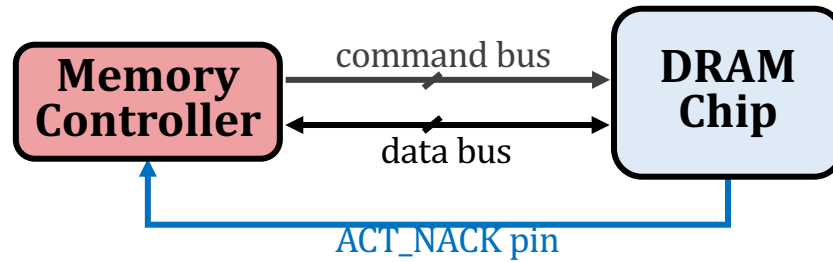
Self-Managing DRAM: Overview

Self-Managing DRAM (SMD)

enables autonomous in-DRAM maintenance operations

Key Idea:

Prevent the memory controller from accessing DRAM regions that are *under maintenance* by **rejecting** row activation (**ACT**) commands



Leveraging the ability to *reject an ACT*, a **maintenance operation** can be implemented **completely within a DRAM chip**

SMD-Based Maintenance Mechanisms

DRAM Refresh

Fixed Rate (SMD-FR)

uniformly refreshes **all** DRAM rows with a **fixed** refresh period

Variable Rate (SMD-VR)

skips refreshing rows that can **retain their data for longer** than the default refresh period

RowHammer Protection

Probabilistic (SMD-PRP)

Performs **neighbor** row refresh with a **small probability** on every row activation

Deterministic (SMD-DRP)

keeps track of most **frequently activated** rows and performs **neighbor** row refresh when activation count threshold is exceeded

Memory Scrubbing

Periodic Scrubbing (SMD-MS)

periodically **scans** the **entire** DRAM for errors and corrects them

Self-Managing DRAM: Summary

The three major DRAM maintenance operations:

- ❖ Refresh
- ❖ RowHammer Protection
- ❖ Memory Scrubbing

Implementing new **maintenance mechanisms** often requires **difficult-to-realize changes**

Our Goal

- ① Ease the process of enabling new DRAM maintenance operations
- ② Enable more efficient in-DRAM maintenance operations

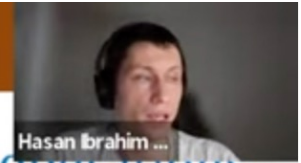
Self-Managing DRAM (SMD)

Enables implementing new **in-DRAM** maintenance mechanisms with **no further changes** in the *DRAM interface* and *memory controller*

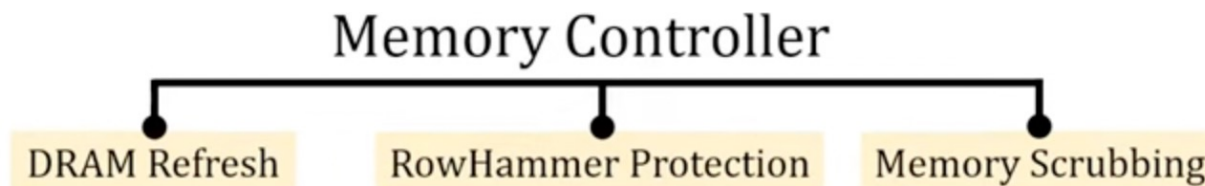
SMD-based *refresh*, *RowHammer protection*, and *scrubbing* achieve **9.2% speedup** and **6.2% lower DRAM energy** vs. conventional DRAM

Talk on Self-Managing DRAM

Problem: The Rigid DRAM Interface



The **Memory Controller** manages DRAM maintenance operations



Changes to maintenance operations are often reflected to the memory controller design, DRAM interface, and other system components



Implementing new maintenance operations
(or modifying the existing ones) is difficult-to-realize



SAFARI Live Seminars 2022

SAFARI Live Seminar - Improving DRAM Performance, Reliability, and Security by Understanding DRAM

1,039 views • Streamed live on Sep 15, 2022

37 DISLIKE SHARE DOWNLOAD CLIP SAVE ...



Onur Mutlu Lectures
27.6K subscribers

ANALYTICS

EDIT VIDEO

ABACuS: Another Intelligent Memory Controller

- Ataberk Olgun, Yahya Can Tugrul, Nisa Bostanci, Ismail Emir Yuksel, Haocong Luo, Steve Rhyner, Abdullah Giray Yaglikci, Geraldo F. Oliveira, and Onur Mutlu,

"ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation"

*To appear in Proceedings of the 33rd USENIX Security Symposium (**USENIX Security**), Philadelphia, PA, USA, August 2024.*

[\[arXiv version\]](#)

[\[ABACuS Source Code\]](#)

ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation

Ataberk Olgun Yahya Can Tugrul Nisa Bostanci Ismail Emir Yuksel
Haocong Luo Steve Rhyner Abdullah Giray Yaglikci Geraldo F. Oliveira Onur Mutlu

ETH Zurich

CoMeT: Another Intelligent Memory Controller

- **To appear at HPCA 2024**

CoMeT: Count-Min-Sketch-based Row Tracking to Mitigate RowHammer at Low Cost

F. Nisa Bostancı İsmail Emir Yüksel Ataberk Olgun Konstantinos Kanellopoulos
Yahya Can Tuğrul A. Giray Yağlıkçı Mohammad Sadrosadati Onur Mutlu
ETH Zürich

Some RowHammer Works in 2024



Session 5B: Rowhammer

Location: Sidlaw

Session Chair: TBD

10:00 AM – 10:20 AM

Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yaglikci, Geraldo Francisco de Oliveira Junior,
Yahya Can Tugrul, Ismail Yuksel, Ataberk Olgun, Haocong Luo,
Onur Mutlu

10:20 AM – 10:40 AM

START: Scalable Tracking for Any Rowhammer Threshold

Anish Saxena, Moinuddin Qureshi

10:40 AM – 11:00 AM

CoMeT: Count-Min Sketch-based Row Tracking to Mitigate RowHammer with Low Cost

Nisa Bostanci, Ismail Emir Yuksel, Ataberk Olgun, Konstantinos
Kanellopoulos, Yahya Can Tugrul, Giray Yaglikci, Mohammad
Sadrosadati, Onur Mutlu



ABACuS: All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation
Ataberk Olgun, Yahya Can Tugrul, Nisa Bostanci, Ismail Emir Yuksel, Haocong Luo, Steve Rhyner, A
Zurich

Go Go Gadget Hammer: Flipping Nested Pointers for Arbitrary Data Leakage
Youssef Tobah, *University of Michigan*; Andrew Kwong, *UNC Chapel Hill*; Ingab Kang
Michigan

SledgeHammer: Amplifying Rowhammer via Bank-level Parallelism
Ingab Kang, *University of Michigan*; Walter Wang and Jason Kim, *Georgia Tech*; Step
Tech; Andrew Kwong, *UNC Chapel Hill*; Yuval Yarom, *Ruhr University Bochum*

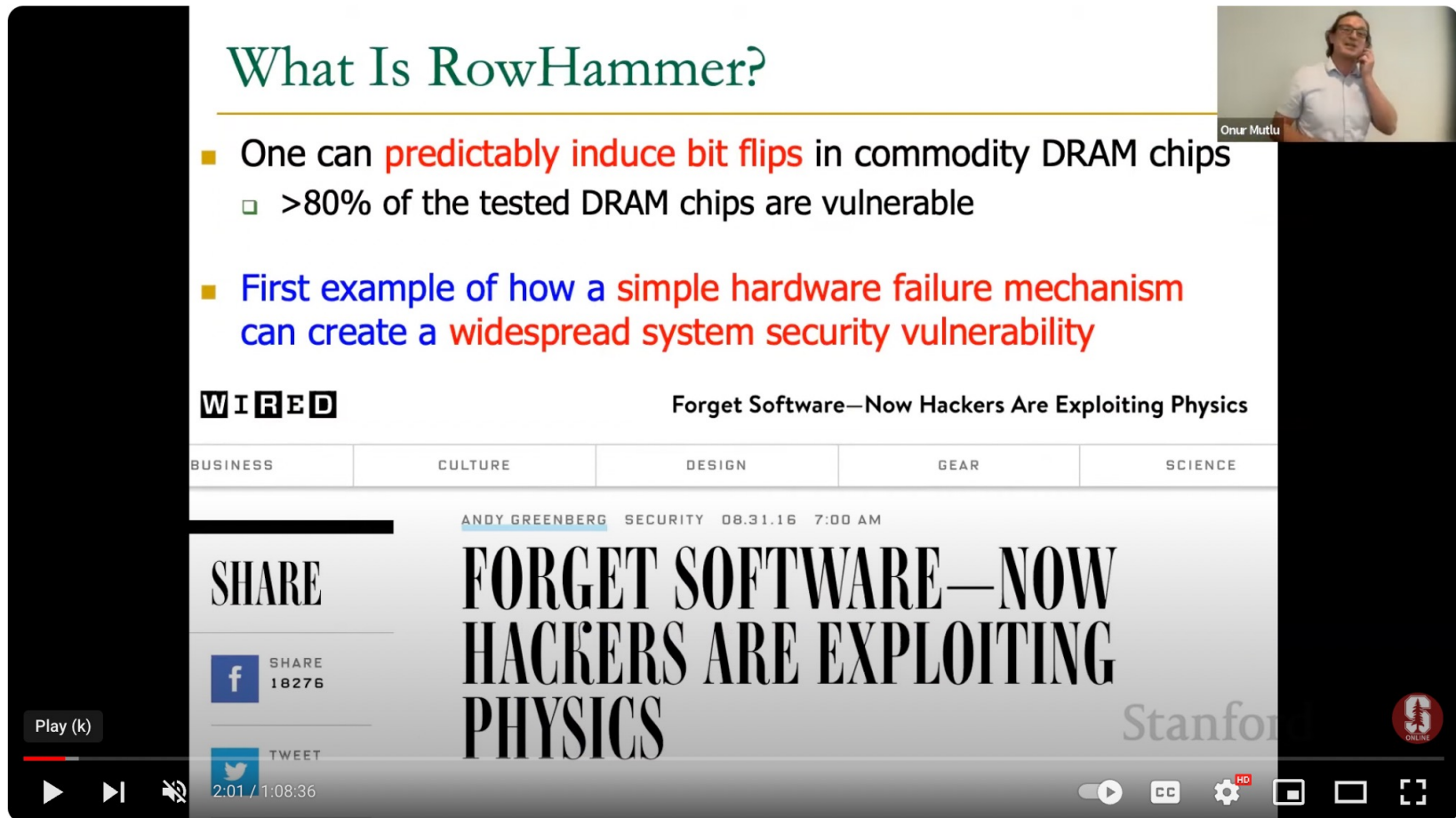
More RowHammer Analysis

- **To appear at HPCA 2024**

Spatial Variation-Aware Read Disturbance Defenses: Experimental Analysis of Real DRAM Chips and Implications on Future Solutions

Abdullah Giray Yağlıkçı Yahya Can Tuğrul Geraldo F. Oliveira
İsmail Emir Yüksel Ataberk Olgun Haocong Luo Onur Mutlu
ETH Zürich

A Recent Detailed RowHammer Lecture



What Is RowHammer?

- One can **predictably induce bit flips** in commodity DRAM chips
 - >80% of the tested DRAM chips are vulnerable
- First example of how a **simple hardware failure mechanism** can create a **widespread system security vulnerability**

WIRED Forget Software—Now Hackers Are Exploiting Physics

BUSINESS CULTURE DESIGN GEAR SCIENCE

ANDY GREENBERG SECURITY 08.31.16 7:00 AM

FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

Stanford Online

1.2K views 1 month ago

Future Memory Robustness Challenges

Future of Main Memory Robustness

- DRAM is becoming less reliable → more vulnerable
- Due to difficulties in DRAM scaling, other problems may also appear (or they may be going unnoticed)
- Some errors may already be slipping into the field
 - Read disturb errors (Rowhammer)
 - Retention errors
 - Read errors, write errors
 - ...
- These errors can also pose security vulnerabilities

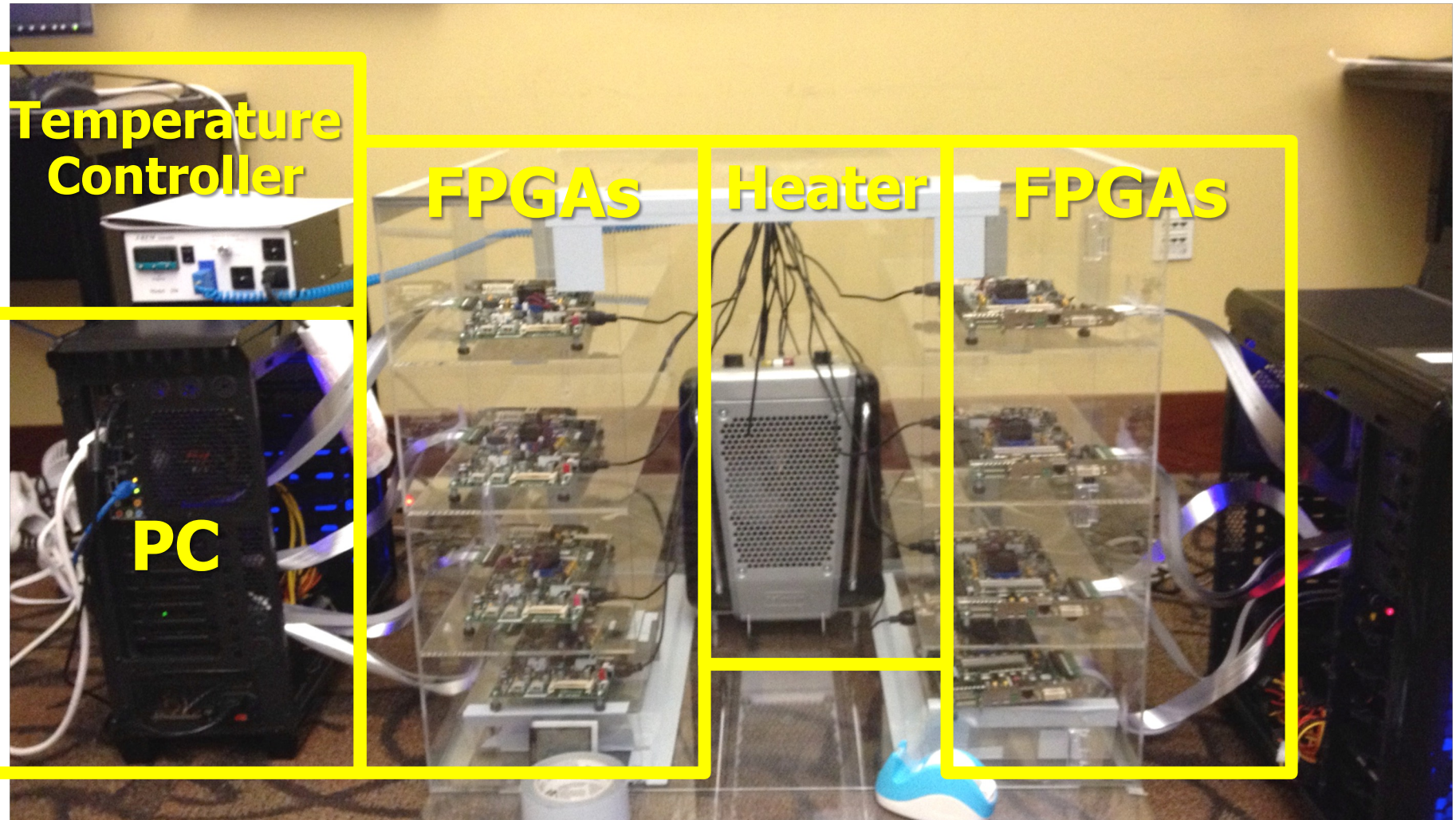
Future of Main Memory Robustness

- DRAM
- Flash memory
- Emerging Technologies
 - Phase Change Memory
 - STT-MRAM
 - RRAM, memristors
 - ...

Architecting Robust Memory Systems

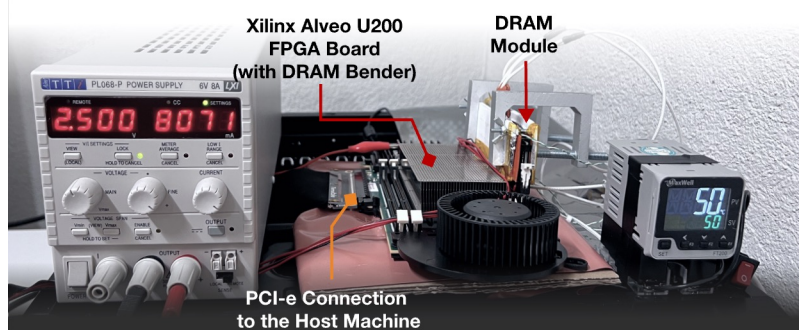
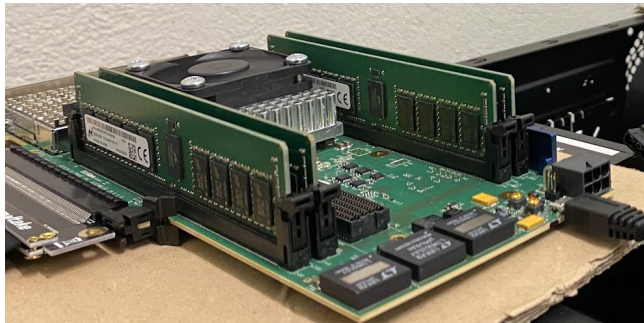
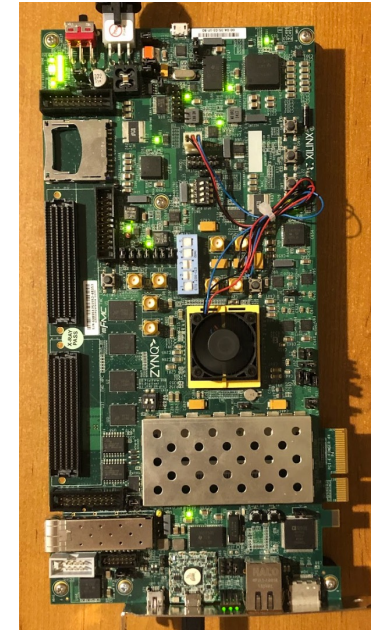
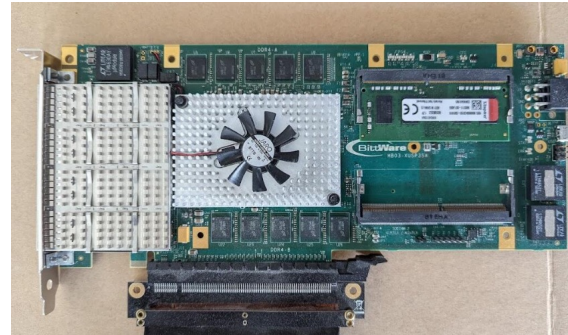
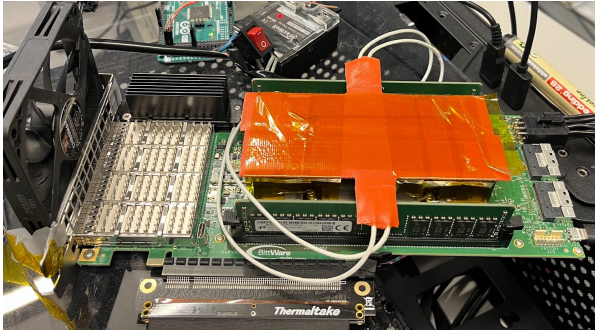
- **Understand:** Methods for vulnerability modeling & discovery
 - Modeling and prediction based on real (device) data and analysis
- **Architect:** Principled architectures with security as key concern
 - Good partitioning of duties across the stack
 - Cannot give up performance and efficiency
 - Patch-ability in the field
- **Design & Test:** Principled design, automation, (online) testing
 - Design for security/safety/reliability
 - High coverage and good interaction with system reliability methods

Understand and Model with Experiments (DRAM)



Understand and Model with Experiments (DRAM)

Five out of the box FPGA-based prototypes



Collapse of the “Galloping Gertie” (1940)



Another Example (1994)



Yet Another Example (2007)



Source: Morry Gash/AP,
<https://www.npr.org/2017/08/01/540669701/10-years-after-bridge-collapse-america-is-still-crumbling?t=1535427165809>

A More Recent Example (2018)



A Most Recent Example (2022)



A Most Recent Example (2022)



A Most Recent Example (2022)



A Most Recent Example (2022)



Intelligent Memory Controllers

Can Avoid Such Failures

Main Memory Needs
Intelligent Controllers
for Security, Safety,
Reliability, Scaling

Fundamentally Robust (Reliable, Secure, Safe) Computing Architectures

Final Thoughts on RowHammer

Before RowHammer (I)

Using Memory Errors to Attack a Virtual Machine

Sudhakar Govindavajhala * Andrew W. Appel
Princeton University
{sudhakar,appel}@cs.princeton.edu

We present an experimental study showing that soft memory errors can lead to serious security vulnerabilities in Java and .NET virtual machines, or in any system that relies on type-checking of untrusted programs as a protection mechanism. Our attack works by sending to the JVM a Java program that is designed so that almost any memory error in its address space will allow it to take control of the JVM. All conventional Java and .NET virtual machines are vulnerable to this attack. The technique of the attack is broadly applicable against other language-based security schemes such as proof-carrying code.

We measured the attack on two commercial Java Virtual Machines: Sun's and IBM's. We show that a single-bit error in the Java program's data space can be exploited to execute arbitrary code with a probability of about 70%, and multiple-bit errors with a lower probability.

Our attack is particularly relevant against smart cards or tamper-resistant computers, where the user has physical access (to the outside of the computer) and can use various means to induce faults; we have successfully used heat. Fortunately, there are some straightforward defenses against this attack.

7 Physical fault injection

If the attacker has physical access to the outside of the machine, as in the case of a smart card or other tamper-resistant computer, the attacker can induce memory errors. We considered attacks on boxes in form factors ranging from a credit card to a palmtop to a desktop PC.

We considered several ways in which the attacker could induce errors.⁴

IEEE S&P 2003

Before RowHammer (II)

Using Memory Errors to Attack a Virtual Machine

Sudhakar Govindavajhala *

Andrew W. Appel

Princeton University

{sudhakar,appel}@cs.princeton.edu

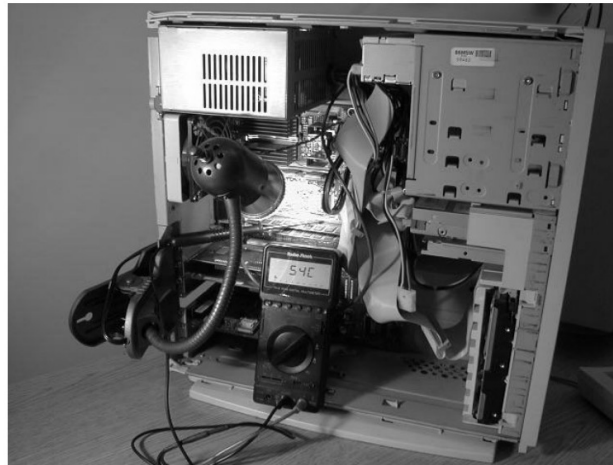


Figure 3. Experimental setup to induce memory errors, showing a PC built from surplus components, clip-on gooseneck lamp, 50-watt spotlight bulb, and digital thermometer. Not shown is the variable AC power supply for the lamp.

IEEE S&P 2003

After RowHammer

A simple, exploitable memory error
can be induced by software

WIRED

Forget Software—Now Hackers Are Exploiting Physics

| | | | | |
|----------|---------|--------|------|---------|
| BUSINESS | CULTURE | DESIGN | GEAR | SCIENCE |
|----------|---------|--------|------|---------|

ANDY GREENBERG SECURITY 08.31.16 7:00 AM

SHARE



SHARE
18276



TWEET

FORGET SOFTWARE—NOW HACKERS ARE EXPLOITING PHYSICS

After RowHammer

A simple, exploitable memory error
can be induced by software



BIZ & IT TECH SCIENCE POLICY CARS GAMING & CULTURE ST

SON OF ROWHAMMER —

There's a new way to flip bits in DRAM, and it works against the latest defenses

New technique produces lots of bitflips and could one day help form an attack.

DAN GOODIN - 10/19/2023, 5:30 AM



RowHammer: Retrospective

- New mindset that has enabled a renewed interest in HW security attack research:
 - ❑ Real (memory) chips are vulnerable, in a simple and widespread manner
→ this causes real security problems
 - ❑ Hardware reliability → security connection is now mainstream discourse
- Many new RowHammer & bitflip attacks...
 - ❑ Tens of papers in top security, architecture, systems venues
 - ❑ **More to come** as RowHammer is getting worse (DDR4 & beyond)
- Many new RowHammer solutions...
 - ❑ Apple security release; Memtest86 updated
 - ❑ Many solution proposals in top venues (latest in HPCA/Usenix Sec 2024)
 - ❑ Principled system-DRAM co-design (in original RowHammer paper)
 - ❑ **More to come...**

Perhaps Most Importantly...

- RowHammer enabled a shift of mindset in mainstream security researchers
 - General-purpose hardware is fallible, in a widespread manner
 - Its problems are exploitable
- This mindset has enabled many systems security researchers to examine hardware in more depth
 - And understand HW's inner workings and vulnerabilities
- It is no coincidence that two of the groups that discovered Meltdown and Spectre heavily worked on RowHammer attacks before
 - **More to come...**

Conclusion

Summary: RowHammer

- Memory reliability is reducing
- Reliability issues open up security and safety vulnerabilities
 - Very hard to defend against
- **Rowhammer is a prime example**
 - First example of how a simple hardware failure mechanism can create a widespread system security vulnerability
 - Implications on system security & safety are tremendous & exciting
- Bad news: RowHammer is getting worse
- **Good news: We have a lot more to do**
 - We are now fully aware hardware is easily fallible
 - We are developing both attacks and defenses
 - We are developing principled models, methodologies, solutions

Acknowledgments

SAFARI

SAFARI Research Group

safari.ethz.ch

Think BIG, Aim HIGH!

<https://safari.ethz.ch>

SAFARI Research Group

Computer architecture, HW/SW, systems, bioinformatics, security, memory

<https://safari.ethz.ch/safari-newsletter-january-2021/>



Think BIG, Aim HIGH!

SAFARI

<https://safari.ethz.ch>

SAFARI Research Group: December 2021

- <https://safari.ethz.ch/safari-newsletter-december-2021/>

SAFARI
SAFARI Research Group

Think Big, Aim High

ETH zürich



View in your browser
December 2021



SAFARI Newsletter June 2023 Edition

- <https://safari.ethz.ch/safari-newsletter-june-2023/>

SAFARI
SAFARI Research Group

Think Big, Aim High

ETH zürich



View in your browser
June 2023



SAFARI Introduction & Research

Computer architecture, HW/SW, systems, bioinformatics, security, memory



Seminar in Computer Architecture - Lecture 5: Potpourri of Research Topics (Spring 2023)



Onur Mutlu Lectures
32.6K subscribers

Subscribed

17



Share

Download

Clip



719 views Streamed 1 month ago Livestream - Seminar in Computer Architecture - ETH Zürich (Spring 2023)

SAFARI
SAFARI Research Group
safari.ethz.ch

THINK BIG, AIM HIGH!

SAFARI

<https://www.youtube.com/watch?v=mV2OuB2djEs>

Referenced Papers, Talks, Artifacts

- All are available at

<https://people.inf.ethz.ch/omutlu/projects.htm>

<https://www.youtube.com/onurmutlulectures>

<https://github.com/CMU-SAFARI/>

Open Source Tools: SAFARI GitHub



SAFARI Research Group at ETH Zurich and Carnegie Mellon University

Site for source code and tools distribution from SAFARI Research Group at ETH Zurich and Carnegie Mellon University.

322 followers ETH Zurich and Carnegie Mellon U... <https://safari.ethz.ch/> omutlu@gmail.com

Overview Repositories 87 Projects Packages People 13

Pinned

ramulator Public

A Fast and Extensible DRAM Simulator, with built-in support for modeling many different DRAM technologies including DDRx, LPDDRx, GDDRx, WIOx, HBMx, and various academic proposals. Described in the...

C++ 446 196

prim-benchmarks Public

PRIM (Processing-In-Memory benchmarks) is the first benchmark suite for a real-world processing-in-memory (PIM) architecture. PRIM is developed to evaluate, analyze, and characterize the first publ...

C 100 40

MQSim Public

MQSim is a fast and accurate simulator modeling the performance of modern multi-queue (MQ) SSDs as well as traditional SATA based SSDs. MQSim faithfully models new high-bandwidth protocol implement...

C++ 219 121

rowhammer Public

Source code for testing the Row Hammer error mechanism in DRAM devices. Described in the ISCA 2014 paper by Kim et al. at http://users.ece.cmu.edu/~omutlu/pub/dram-row-hammer_isca14.pdf.

C 208 42

SoftMC Public

SoftMC is an experimental FPGA-based memory controller design that can be used to develop tests for DDR3 SODIMMs using a C++ based API. The design, the interface, and its capabilities and limitatio...

Verilog 103 26

Pythia Public

A customizable hardware prefetching framework using online reinforcement learning as described in the MICRO 2021 paper by Bera et al. (<https://arxiv.org/pdf/2109.12021.pdf>).

C++ 86 26

Ramulator 2.0

- Haocong Luo, Yahya Can Tugrul, F. Nisa Bostanci, Ataberk Olgun, A. Giray Yaglikci, and Onur Mutlu,
"Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator"
*Preprint on **arxiv**, August 2023.*
[[arXiv version](#)]
[[Ramulator 2.0 Source Code](#)]

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

<https://arxiv.org/pdf/2308.11030.pdf>

DRAM Bender

- Ataberk Olgun, Hasan Hassan, A Giray Yağlıkçı, Yahya Can Tuğrul, Lois Orosa, Haocong Luo, Minesh Patel, Oğuz Ergin, and Onur Mutlu,
"DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips"
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD), 2023.
[[Extended arXiv version](#)]
[[DRAM Bender Source Code](#)]
[[DRAM Bender Tutorial Video](#) (43 minutes)]

DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips

Ataberk Olgun[§] Hasan Hassan[§] A. Giray Yağlıkçı[§] Yahya Can Tuğrul^{§†}
Lois Orosa^{§⊙} Haocong Luo[§] Minesh Patel[§] Oğuz Ergin[†] Onur Mutlu[§]
 [§]*ETH Zürich* [†]*TOBB ETÜ* [⊙]*Galician Supercomputing Center*

RowHammer & DRAM Exploration (Fall 2022)

Fall 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=softmc

Spring 2022 Edition:

- ❑ https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=softmc

Youtube Livestream (Spring 2022):

- ❑ https://www.youtube.com/watch?v=r5QxuoJWttg&list=PL5Q2soXY2Zi_1trfCckr6PTN8WR72icUO

Bachelor's course

- ❑ Elective at ETH Zurich
- ❑ Introduction to DRAM organization & operation
- ❑ Tutorial on using FPGA-based infrastructure
- ❑ Verilog & C++
- ❑ Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

| Week | Date | Livestream | Meeting | Learning Materials | Assignments |
|------|---------------|------------|---|---|-------------|
| W0 | 23.02 Wed. | | P&S SoftMC Tutorial | SoftMC Tutorial Slides (PDF) (PPT) | |
| W1 | 08.03 Tue. | | M1: Logistics & Intro to DRAM and SoftMC (PDF) (PPT) | Required Materials Recommended Materials | HW0 |
| W2 | 15.03 Tue. | | M2: Revisiting RowHammer (PDF) (PPT) | (Paper PDF) | |
| W3 | 22.03 Tue. | | M3: Uncovering in-DRAM TRR & TRRespass (PDF) (PPT) | | |
| W4 | 29.03 Tue. | | M4: Deeper Look Into RowHammer's Sensitivities (PDF) (PPT) | | |
| W5 | 05.04 Tue. | | M5: QUAC-TRNG (PDF) (PPT) | | |
| W6 | 12.04 Tue. | | M6: PiDRAM (PDF) (PPT) | | |

Exploration of Emerging Memory Systems (Fall 2022)

Fall 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator

Spring 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator

Youtube Livestream (Spring 2022):

- https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZApgV

Bachelor's course

- Elective at ETH Zurich
- Introduction to memory system simulation
- Tutorial on using Ramulator
- C++
- Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

| Week | Date | Livestream | Meeting | Learning Materials | Assignments |
|------|------------|---|--|--------------------|-------------|
| W1 | 09.03 Wed. | YouTube Video | M1: Logistics & Intro to Simulating Memory Systems Using Ramulator PDF (PDF) PPT (PPT) | | HW0 |
| W2 | 16.03 Fri. | YouTube Video | M2: Tutorial on Using Ramulator PDF (PDF) PPT (PPT) | | |
| W3 | 25.02 Fri. | YouTube Video | M3: BlockHammer PDF (PDF) PPT (PPT) | | |
| W4 | 01.04 Fri. | YouTube Video | M4: CLR-DRAM PDF (PDF) PPT (PPT) | | |
| W5 | 08.04 Fri. | YouTube Video | M5: SIMDRAM PDF (PDF) PPT (PPT) | | |
| W6 | 29.04 Fri. | YouTube Video | M6: DAMOV PDF (PDF) PPT (PPT) | | |
| W7 | 06.05 Fri. | YouTube Video | M7: Synchron PDF (PDF) PPT (PPT) | | |



RowHammer, RowPress & Beyond

Can We Be Free of Bitflips (Soon)?

Onur Mutlu

omutlu@gmail.com

<https://people.inf.ethz.ch/omutlu>

28 February 2024

UC Berkeley

SAFARI

ETH zürich

Carnegie Mellon

More RowHammer in 2020-2023

RowHammer in 2020 (I)

MICRO 2020

Submit Work ▾

Program ▾

Attend

Session 1A: Security & Privacy I

5:00 PM CEST – 5:15 PM CEST

Graphene: Strong yet Lightweight Row Hammer Protection

Yeonhong Park, Woosuk Kwon, Eojin Lee, Tae Jun Ham, Jung Ho Ahn, Jae W. Lee (Seoul National University)

5:15 PM CEST – 5:30 PM CEST

Persist Level Parallelism: Streamlining Integrity Tree Updates for Secure Persistent Memory

Alexander Freij, Shougang Yuan, Huiyang Zhou (NC State University); Yan Solihin (University of Central Florida)

5:30 PM CEST – 5:45 PM CEST

PThammer: Cross-User-Kernel-Boundary Rowhammer through Implicit Accesses

Zhi Zhang (University of New South Wales and Data61, CSIRO, Australia); Yueqiang Cheng (Baidu Security); Dongxi Liu, Surya Nepal (Data61, CSIRO, Australia); Zhi Wang (Florida State University); Yuval Yarom (University of Adelaide and Data61, CSIRO, Australia)

RowHammer in 2020 (II)

S & P

Home

Program ▼

Call For... ▼

Attend ▼

Workshops ▼

Session #5: Rowhammer

Room 2

Session chair: Michael Franz (UC Irvine)

RAMBleed: Reading Bits in Memory Without Accessing Them

Andrew Kwong (University of Michigan), Daniel Genkin (University of Michigan), Daniel Gruss (Data61)

Are We Susceptible to Rowhammer? An End-to-End Methodology for Cloud Providers

Lucian Cojocar (Microsoft Research), Jeremie Kim (ETH Zurich, CMU), Minesh Patel (ETH Zurich, Microsoft Research), Onur Mutlu (ETH Zurich, CMU)

Leveraging EM Side-Channel Information to Detect Rowhammer Attacks

Zhenkai Zhang (Texas Tech University), Zihao Zhan (Vanderbilt University), Daniel Balasubramanian (Vanderbilt University), Peter Volgyesi (Vanderbilt University), Xenofon Koutsoukos (Vanderbilt University)

TRRespass: Exploiting the Many Sides of Target Row Refresh

Pietro Frigo (Vrije Universiteit Amsterdam, The Netherlands), Emanuele Vannacci (Vrije Universiteit Amsterdam, The Netherlands), Onur Mutlu (ETH Zürich), Cristiano Giuffrida (Vrije Universiteit Amsterdam, The Netherlands), Kaveh Razavi (Vrije Universiteit Amsterdam, The Netherlands)

RowHammer in 2020 (III)

29TH USENIX
SECURITY SYMPOSIUM

ATTEND

PROGRAM

PARTICIPATE

SPONSORS

ABOUT

DeepHammer: Depleting the Intelligence of Deep Neural Networks through Targeted Chain of Bit Flips

Fan Yao, *University of Central Florida*; Adnan Siraj Rakin and Deliang Fan, *Arizona State University*

AVAILABLE MEDIA   

Show details ▶

RowHammer in 2020 (IV)

■ CHES 2020

JackHammer: Efficient Rowhammer on Heterogeneous FPGA-CPU Platforms

Zane Weissman¹, Thore Tiemann², Daniel Moghimi¹, Evan Custodio³,
Thomas Eisenbarth² and Berk Sunar¹

¹ Worcester Polytechnic Institute, MA, USA

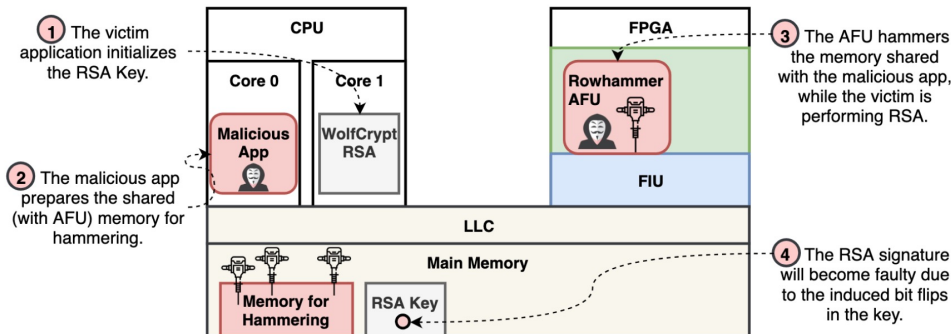
zweissman@wpi.edu, amoghimi@wpi.edu, sunar@wpi.edu

² University of Lübeck, Lübeck, Germany

thore.tiemann@student.uni-luebeck.de, thomas.eisenbarth@uni-luebeck.de

³ Intel Corporation, Hudson, MA, USA

evan.custodio@intel.com



An **FPGA-based** RowHammer attack recovering **private keys** twice as fast compared to **CPU-based** attacks

RowHammer in 2021 (I)

HotOS XVIII

The 18th Workshop on Hot Topics in Operating Systems

31-May 1 June–3 June 2021, Cyberspace, People's Couches, and Zoom

Stop! Hammer Time: Rethinking Our Approach to Rowhammer Mitigations

RowHammer in 2021 (II)

SMASH: Synchronized Many-sided Rowhammer Attacks from JavaScript

RowHammer in 2021 (III)



Session 10A: Security & Privacy III

Session Chair: Hoda Naghibijouybari (Binghamton)

9:00 PM CEST – 9:15 PM CEST

A Deeper Look into RowHammer's Sensitivities: Experimental Analysis of Real DRAM Chips and Implications on Future Attacks and Defenses

Lois Orosa, Abdullah Giray Yaglikci, Haocong Luo (ETH Zurich); Ataberk Olgun (TOBB University of Economics and Technology); Jisung Park, Hasan Hassan, Minesh Patel, Jeremie S. Kim, Onur Mutlu (ETH Zurich)

 [Paper](#)

9:15 PM CEST – 9:30 PM CEST

Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications

Hasan Hassan (ETH Zurich); Yahya Can Tugrul (TOBB University of Economics and Technology); Jeremie S. Kim (ETH Zurich); Victor van der Veen (Qualcomm); Kaveh Razavi, Onur Mutlu (ETH Zurich)

 [Paper](#)

RowHammer in 2022 (I)

MAY 22-26, 2022 AT THE HYATT REGENCY, SAN FRANCISCO, CA

43rd IEEE Symposium on Security and Privacy

BLACKSMITH: Scalable Rowhammering in the Frequency Domain

**SpecHammer: Combining Spectre and Rowhammer
for New Speculative Attacks**

**PROTRR: Principled yet Optimal In-DRAM
Target Row Refresh**

**DeepSteal: Advanced Model Extractions Leveraging Efficient
Weight Stealing in Memories**

RowHammer in 2022 (II)



Randomized Row-Swap: Mitigating Row Hammer by Breaking Spatial Correlation between Aggressor and Victim Rows

RowHammer in 2022 (III)

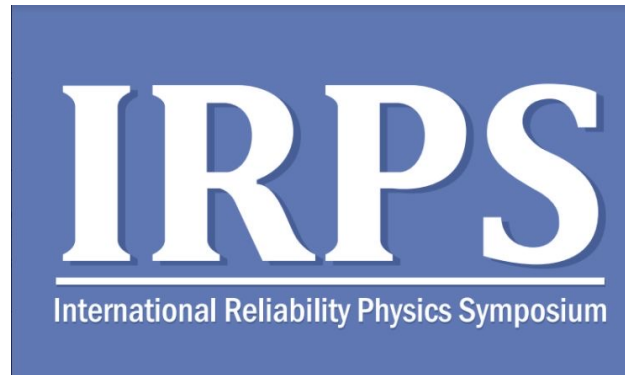
HPCA 2022

The 28th IEEE International Symposium on High-Performance Computer Architecture (HPCA-28), Seoul, South Korea

SafeGuard: Reducing the Security Risk from Row-Hammer via Low-Cost Integrity Protection

Mithril: Cooperative Row Hammer Protection on Commodity DRAM Leveraging Managed Refresh

RowHammer in 2022 (IV)



IRPS 2022

The Price of Secrecy: How Hiding Internal DRAM Topologies Hurts Rowhammer Defenses

Stefan Saroiu, Alec Wolman, Lucian Cojocar
Microsoft

RowHammer in 2022 (V)



Half-Double: Hammering From the Next Row Over

Andreas Kogler¹ Jonas Juffinger^{1,2} Salman Qazi³ Yoongu Kim³ Moritz Lipp^{4*}
Nicolas Boichat³ Eric Shiu⁵ Mattias Nissler³ Daniel Gruss¹

¹*Graz University of Technology* ²*Lamarr Security Research* ³*Google*
⁴*Amazon Web Services* ⁵*Rivos*

RowHammer in 2022 (VI)



HAMMERSCOPE: Observing DRAM Power Consumption Using Rowhammer

**When Frodo Flips:
End-to-End Key Recovery on FrodoKEM via Rowhammer**

RowHammer in 2022 (VII)



AQUA: Scalable Rowhammer Mitigation by Quarantining Aggressor Rows at Runtime

Anish Saxena, Gururaj Saileshwar (Georgia Institute of Technology); Prashant J. Nair (University of British Columbia); Moinuddin Qureshi (Georgia Institute of Technology)

HiRA: Hidden Row Activation for Reducing Refresh Latency of Off-the-Shelf DRAM Chips

Abdullah Giray Yaglikci (ETH Zürich); Ataberk Olgun (TOBB University of Economics and Technology); Lois Orosa, Minesh Patel, Haocong Luo, Hasan Hassan (ETH Zürich); Oguz Ergin (TOBB University of Economics and Technology); Onur Mutlu (ETH Zürich)

RowHammer in 2022 (VII)

- A. Giray Yaglikci, Ataberk Olgun, Minesh Patel, Haocong Luo, Hasan Hassan, Lois Orosa, Oguz Ergin, and Onur Mutlu,
"HiRA: Hidden Row Activation for Reducing Refresh Latency of Off-the-Shelf DRAM Chips"
Proceedings of the 55th International Symposium on Microarchitecture (MICRO),
Chicago, IL, USA, October 2022.
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Longer Lecture Slides \(pptx\)](#)] [[pdf](#)]
[[Lecture Video](#) (36 minutes)]
[[arXiv version](#)]

HiRA: Hidden Row Activation for Reducing Refresh Latency of Off-the-Shelf DRAM Chips

A. Giray Yağlıkçı¹ Ataberk Olgun^{1,2} Minesh Patel¹ Haocong Luo¹ Hasan Hassan¹
Lois Orosa^{1,3} Oğuz Ergin² Onur Mutlu¹

¹ETH Zürich

²TOBB University of Economics and Technology

³Galicia Supercomputing Center (CESGA)

<https://arxiv.org/pdf/2209.10198.pdf>

RowHammer in 2022 (VIII)

A Case for Transparent Reliability in DRAM Systems

Minesh Patel[†] Taha Shahroodi^{‡‡} Aditya Manglik[†] A. Giray Yağlıkçı[†]
Ataberk Olgun[†] Haocong Luo[†] Onur Mutlu[†]

[†]*ETH Zürich* [‡]*TU Delft*

<https://arxiv.org/pdf/2204.10378.pdf>

RowHammer in 2022 (IX)

A Case for Self-Managing DRAM Chips: Improving Performance, Efficiency, Reliability, and Security via Autonomous in-DRAM Maintenance Operations

Hasan Hassan

Ataberk Olgun

A. Giray Yağlıkçı

Haocong Luo

Onur Mutlu

ETH Zürich

<https://arxiv.org/pdf/2207.13358.pdf>

RowHammer in 2023 (I)

MAY 22-26, 2023 AT THE HYATT REGENCY, SAN FRANCISCO, CA

44th IEEE Symposium on Security and Privacy

Session 6C: Rowhammer and spectre

Bayview AB

11:00 AM – 12:15 PM

Session Chair: Eyal Ronen

REGA: Scalable Rowhammer Mitigation with Refresh-Generating Activations

Michele Marazzi (ETH Zurich), Flavien Solt (ETH Zurich), Patrick Jattke (ETH Zurich), Kubo Takashi (Zentel Japan), Kaveh Razavi (ETH Zurich)

CSI:Rowhammer - Cryptographic Security and Integrity against Rowhammer

Jonas Juffinger (Lamarr Security Research, Graz University of Technology, Austria), Lukas Lamster (Graz University of Technology, Austria), Andreas Kogler (Graz University of Technology, Austria), Maria Eichlseder (Graz University of Technology, Austria), Moritz Lipp (Amazon Web Services, Austria), Daniel Gruss (Graz University of Technology, Austria)

Jolt: Recovering TLS Signing Keys via Rowhammer Faults

Koksal Mus (Worcester Polytechnic Institute), Yarkin Doröz (Worcester Polytechnic Institute), M. Caner Tol (Worcester Polytechnic Institute), Kristi Rahman (Worcester Polytechnic Institute), Berk Sunar (Worcester Polytechnic Institute)

RowHammer in 2023 (II)

HPCA 2023

The 29th IEEE International Symposium on High-Performance Computer Architecture (HPCA-29)

**Scalable and Secure Row-Swap:
Efficient and Safe Row Hammer
Mitigation in Memory Systems**

*Jeonghyun Woo (University of
British Columbia),
Gururaj Saileshwar (Georgia
Institute of Technology),
Prashant J. Nair (University of
British Columbia)*

**SHADOW: Preventing Row
Hammer in DRAM with Intra-
Subarray Row Shuffling**

*Minbok Wi (Seoul National
University),
Jaehyun Park (Seoul National
University),
Seoyoung Ko (Seoul National
University), Michael Jaemin Kim
(Seoul National University),
Nam Sung Kim (UIUC),
Eojin Lee (Inha University),
Jung Ho Ahn (Seoul National
University)*

RowHammer in 2023 (III): SK Hynix

ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES /

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyong Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

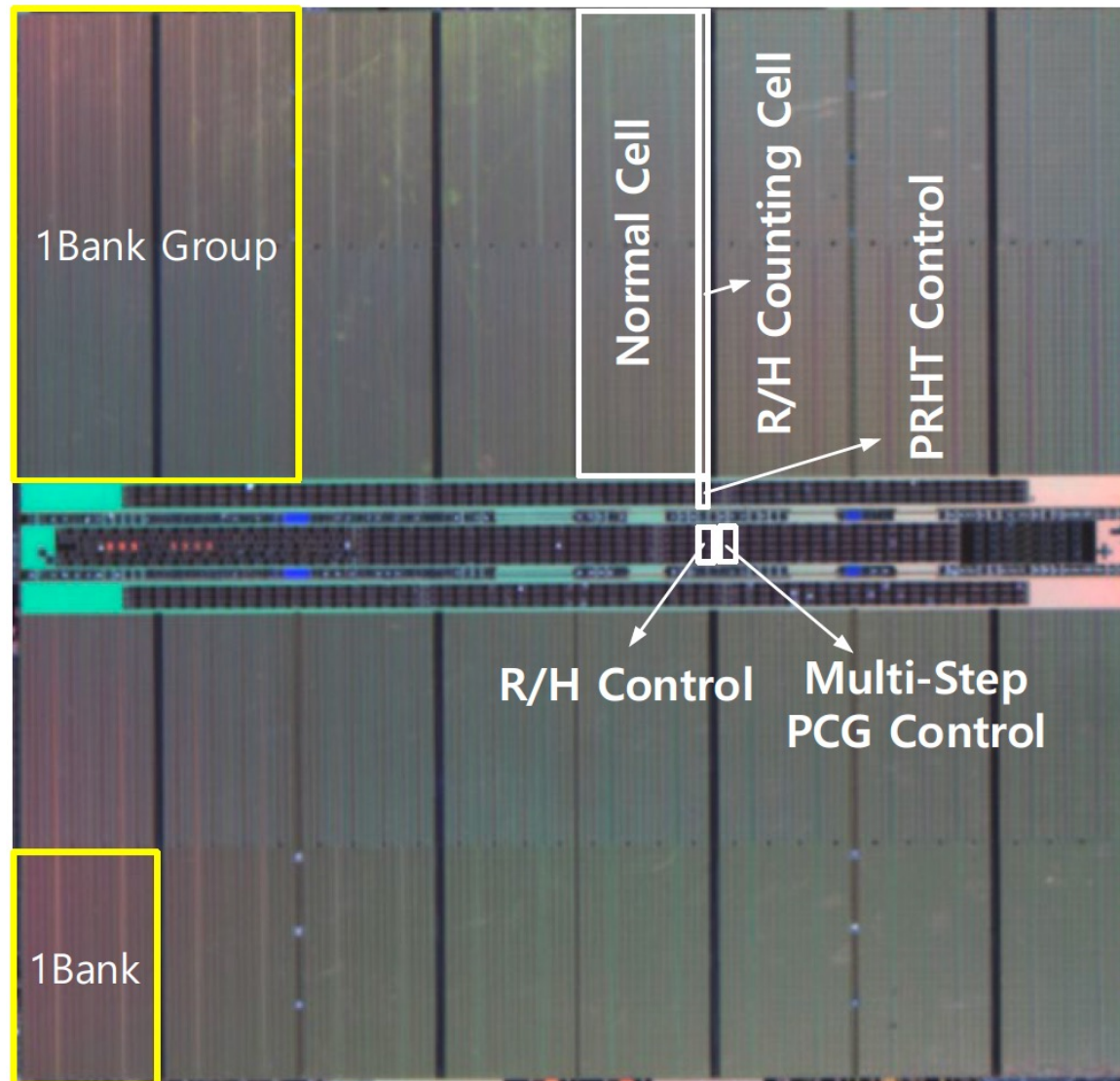


Industry's RowHammer Solutions (I)

SK hynix Semiconductor, Icheon, Korea

DRAM products have been recently adopted in a wide range of high-performance computing applications: such as in cloud computing, in big data systems, and IoT devices. This demand creates larger memory capacity requirements, thereby requiring aggressive DRAM technology node scaling to reduce the cost per bit [1,2]. However, DRAM manufacturers are facing technology scaling challenges due to row hammer and refresh retention time beyond 1a-nm [2]. Row hammer is a failure mechanism, where repeatedly activating a DRAM row disturbs data in adjacent rows. Scaling down severely threatens reliability since a reduction of DRAM cell size leads to a reduction in the intrinsic row hammer tolerance [2,3]. To improve row hammer tolerance, there is a need to probabilistically activate adjacent rows with carefully sampled active addresses and to improve intrinsic row hammer tolerance [2]. In this paper, row-hammer-protection and refresh-management schemes are presented to guarantee DRAM security and reliability despite the aggressive scaling from 1a-nm to sub 10-nm nodes. The probabilistic-aggressor-tracking scheme with a refresh-management function (RFM) and per-row hammer tracking (PRHT) improve DRAM resilience. A multi-step precharge reinforces intrinsic row-hammer tolerance and a core-bias modulation improves retention time: even in the face of cell-transistor degradation due to technology scaling. This comprehensive scheme leads to a reduced probability of failure, due to row hammer attacks, by 93.1% and an improvement in retention time by 17%.

Industry's RowHammer Solutions (II)



ISSCC 2023 / SESSION 28 / HIGH-DENSITY MEMORIES

28.8 A 1.1V 16Gb DDR5 DRAM with Probabilistic-Aggressor Tracking, Refresh-Management Functionality, Per-Row Hammer Tracking, a Multi-Step Precharge, and Core-Bias Modulation for Security and Reliability Enhancement

Woongrae Kim, Chulmoon Jung, Seongnyuh Yoo, Duckhwa Hong, Jeongjin Hwang, Jungmin Yoon, Ohyoung Jung, Joonwoo Choi, Sanga Hyun, Mankeun Kang, Sangho Lee, Dohong Kim, Sanghyun Ku, Donhyun Choi, Nogeun Joo, Sangwoo Yoon, Junseok Noh, Byeongyong Go, Cheolhoe Kim, Sunil Hwang, Mihyun Hwang, Seol-Min Yi, Hyungmin Kim, Sanghyuk Heo, Yeonsu Jang, Kyoungchul Jang, Shinho Chu, Yoonna Oh, Kwidong Kim, Junghyun Kim, Soohwan Kim, Jeongtae Hwang, Sangil Park, Junphyo Lee, Inchul Jeong, Joohwan Cho, Jonghwan Kim

SK hynix Semiconductor, Icheon, Korea

RowHammer in 2023 (IV): Samsung

DSAC: Low-Cost Rowhammer Mitigation Using In-DRAM Stochastic and Approximate Counting Algorithm

Seungki Hong Dongha Kim Jaehyung Lee Reum Oh
Changsik Yoo Sangjoon Hwang Jooyoung Lee

DRAM Design Team, Memory Division, Samsung Electronics

<https://arxiv.org/pdf/2302.03591v1.pdf>

RowHammer in 2023 (V)



[28 June, 14:30-16:00] RT-3: Memory 1 (Session Chair: TBD)

Compiler-Implemented Differential Checksums: Effective Detection and Correction of Transient and Permanent Memory Errors (REG)

C. Borchert; H. Schirmeier; O. Spinczyk

PT-Guard: Integrity-Protected Page Tables to Defend Against Breakthrough Rowhammer Attacks (REG)

A. Saxena; G. Saileshwar; J. Juffinger; A. Kogler; D. Gruss; M. Qureshi

Don't Knock! Rowhammer at the Backdoor of DNN Models (REG)

M. Tol; S. Islam; A. Adiletta; B. Sunar; Z. Zhang

[29 June, 16:00-17:30] DS23-4: Hardware Resilience and Human Factors (Session Chair: TBD)

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun, Majd Osseiran, Abdullah Giray Yaglikci, Yahya Can Tugrul, Juan Gomez Luna, Haocong Luo, Behzad Salami, Steve Rhyner and Onur Mutlu

RowHammer in 2023 (VI)

■ SOSP 2023

SOSP 2023

The 29th ACM Symposium on Operating Systems Principles
October 23-26, 2023

Siloz: Leveraging DRAM Isolation Domains to Prevent Inter-VM Rowhammer

Kevin Loughlin
University of Michigan

Jonah Rosenblum
University of Michigan

Stefan Saroiu
Microsoft

Alec Wolman
Microsoft

Dimitrios Skarlatos
Carnegie Mellon University

Baris Kasikci
University of Washington and Google

RowHammer in 2023 (VII)

- IEEE Computer Architecture Letters, 2023

NoHammer: Preventing Row Hammer with Last-Level Cache Management

Seunghak Lee, Ki-Dong Kang, Gyeongseo Park, Nam Sung Kim, and Daehoon Kim

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

- IEEE Embedded Systems Letters, 2023

Flipping Bits Like a Pro: Precise Rowhammering on Embedded Devices

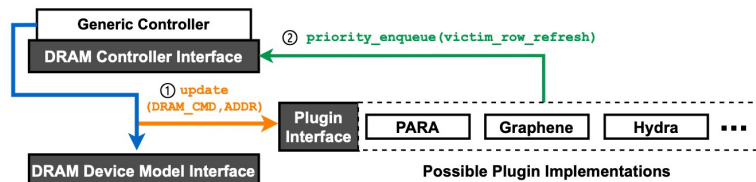
Anandpreet Kaur, Pravin Srivastav, Bibhas Ghoshal
Systems Lab, Indian Institute of Information Technology Allahabad (IIITA)

Ramulator 2.0

"Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator"

IEEE Computer Architecture Letters, August 2023. (*Preprint on **arxiv***)

[[arXiv version](#)] [[Ramulator 2.0 Source Code](#)]



CMU-SAFARI / ramulator2 Public

Notifications Fork 15 Star 68

<> Code Issues 7 Pull requests Actions Projects Security Insights

main 1 branch 0 tags Go to file Code About

Haocong Luo Fix bug in LDST trace frontend (Issu... 58f2819 3 weeks ago 22 commits

| | | |
|------------------------|--|--------------|
| perf_comparison | Add missing files. | 3 weeks ago |
| resources/gem5_wrap... | Add missing files. | 3 weeks ago |
| rh_study | Init | 2 months ago |
| src | Fix bug in LDST trace frontend (Issue #10) | 3 weeks ago |
| verilog_verification | Init | 2 months ago |

Ramulator 2.0 is a modern, modular, extensible, and fast cycle-accurate DRAM simulator. It provides support for agile implementation and evaluation of new memory system designs (e.g., new DRAM standards, emerging RowHammer mitigation techniques). Described in our paper https://people.inf.ethz.ch/omutlu/pub/Ramulator2_arxiv23.pdf

Ramulator 2.0: A Modern, Modular, and Extensible DRAM Simulator

Haocong Luo, Yahya Can Tuğrul, F. Nisa Bostancı, Ataberk Olgun, A. Giray Yağlıkçı, and Onur Mutlu

RowHammer in 2023 (VIII)

■ MEMSYS 2023

RAMPART: RowHammer Mitigation and Repair for Server Memory Systems

Steven C. Woo
Rambus Labs
Rambus Inc.
San Jose, CA
swoo@rambus.com

Wendy Elsasser
Rambus Labs
Rambus Inc.
San Jose, CA
welsasser@rambus.com

Mike Hamburg
Rambus Labs
Rambus Inc.
San Jose, CA
hamburg@rambus.com

Eric Linstadt
Rambus Labs
Rambus Inc.
San Jose, CA
elinstadt@rambus.com

Michael R. Miller
Rambus Labs
Rambus Inc.
San Jose, CA
michaelm@rambus.com

Taeksang Song
Rambus Labs
Rambus Inc.
San Jose, CA
tsong@rambus.com

James Tringali
Rambus Labs
Rambus Inc.
San Jose, CA
jamestr@rambus.com

■ MICRO 2023

How to Kill the Second Bird with One ECC: The Pursuit of Row Hammer Resilient DRAM

Michael Jaemin Kim, Minbok Wi, Jaehyun Park, Seoyoung Ko, Jae Young Choi, Hwayoung Nam (Seoul National University); Nam Sung Kim (University of Illinois Urbana Champaign); Jung Ho Ahn (Seoul National University); Eojin Lee (Inha University)

Related Courses

DDCA (Spring 2022)

Spring 2022 Edition:

- <https://safari.ethz.ch/digitaltechnik/spring2022/duku.php?id=schedule>

Spring 2021 Edition:

- <https://safari.ethz.ch/digitaltechnik/spring2021/duku.php?id=schedule>

Youtube Livestream (Spring 2022):

- <https://www.youtube.com/watch?v=cpXdE3HwvK0&list=PL5Q2soXY2Zi97Ya5DEUpMpO2bbAoaG7c6>

Youtube Livestream (Spring 2021):

- https://www.youtube.com/watch?v=LbC0EZY8yw4&list=PL5Q2soXY2Zi_uej3aY39YB5pfW4SJ7LIN

Bachelor's course

- 2nd semester at ETH Zurich
- Rigorous introduction into "How Computers Work"
- Digital Design/Logic
- Computer Architecture
- 10 FPGA Lab Assignments

<https://www.youtube.com/onurmutlulectures>



Trace: - schedule

Home

Announcements

Materials

- Lectures/Schedule
- Lecture Buzzwords
- Readings
- Optional HWs
- Labs
- Extra Assignments
- Exams
- Technical Docs

Resources

- Computer Architecture (CMU) SS15: Lecture Videos
- Computer Architecture (CMU) SS15: Course Website
- Digitaltechnik SS18: Lecture Videos
- Digitaltechnik SS18: Course Website
- Digitaltechnik SS19: Lecture Videos
- Digitaltechnik SS19: Course Website
- Digitaltechnik SS20: Lecture Videos
- Digitaltechnik SS20: Course Website
- Moodle

Lecture Video Playlist on YouTube

Livestream Lecture Playlist

Onur Mutlu: Digital Design and Computer Architecture Today

- Computing landscape is very different from 10-20 years ago
- Applications and technology both demand novel architectures

Watch on YouTube

Recorded Lecture Playlist

Digital Design & Computer Architecture: Lect...

How Computers Work


(from the ground up)

Watch on YouTube

Spring 2021 Lectures/Schedule

| Week | Date | Livestream | Lecture | Readings | Lab | HW |
|------|------------|--------------|---|------------------------------------|-----|----|
| W1 | 25.02 Thu. | YouTube Live | L1: Introduction and Basics G2a (PDF) G2a (PPT) | Required Suggested Mentioned | | |
| | 26.02 Fri. | YouTube Live | L2a: Tradeoffs, Metrics, Mindset G2a (PDF) G2a (PPT) | Required | | |
| | | | L2b: Mysteries in Computer Architecture G2a (PDF) G2a (PPT) | Required Mentioned | | |
| W2 | 04.03 Thu. | YouTube Live | L3a: Mysteries in Computer Architecture II G2a (PDF) G2a (PPT) | Required Suggested Mentioned | | |

Comp Arch (Fall 2022)



Computer Architecture - Fall 2022

Recent Changes Media Manager Sitemap

Trace: start schedule

Home

Announcements

Materials

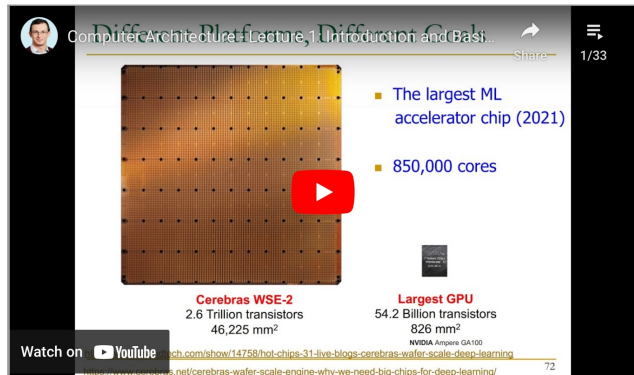
- Lectures/Schedule
- Lecture Buzzwords
- Readings
- HWs
- Exams
- Related Courses
- Tutorials

Resources

- Computer Architecture FS21: Course Webpage
- Computer Architecture FS21: Lecture Videos
- Digitaltechnik SS21: Course Webpage
- Digitaltechnik SS21: Lecture Videos
- Moodle
- HotCRP
- Verilog Practice Website (HDLBits)

Lecture Video Playlist on YouTube

Livestream Lecture Playlist

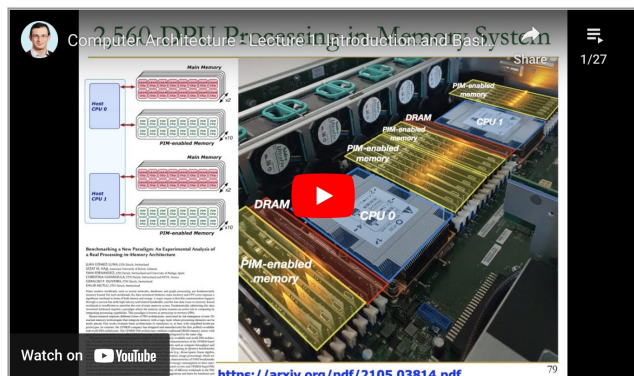


The largest ML accelerator chip (2021)

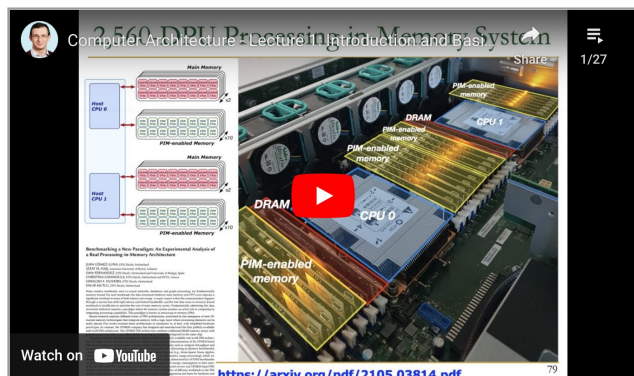
850,000 cores

Cerebras WSE-2
2.6 Trillion transistors
46,225 mm²

Largest GPU
54.2 Billion transistors
826 mm²
NVIDIA Ampere GA100












Watch on  [ch.com/show/14756/hot-chips-31-live-blogs-cerebras-wse-2-why-we-need-big-chips-for-deep-learning](https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF)

Lecture Playlist from Fall 2021



<https://arxiv.org/pdf/2105.03814.pdf>

Fall 2022 Lectures & Schedule

| Week | Date | Livestream | Lecture | Readings | Lab | HW |
|------|------------|--|---|---------------------|-----------|----------|
| W1 | 29.09 Thu. |  Live | L1: Introduction and Basics  (PDF)  (PPT) | Required Mentioned | Lab 1 Out | HW 0 Out |
| | 30.09 Fri. |  Live | L2a: Memory Systems: Challenges and Opportunities  (PDF)  (PPT) L2b: Course Info & Logistics  (PDF)  (PPT) | Described Suggested | | |
| W2 | 06.10 Thu. |  Live | L3: Processing using Memory  (PDF)  (PPT) | Described Suggested | | HW 1 Out |

Fall 2022 Edition:

□ <https://safari.ethz.ch/architecture/fall2022/doku.php?id=schedule>

Fall 2021 Edition:

□ <https://safari.ethz.ch/architecture/fall2021/doku.php?id=schedule>

Youtube Livestream (2022):

□ https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF

Youtube Livestream (2021):

□ https://www.youtube.com/watch?v=4yfkM_5EFgo&list=PL5Q2soXY2Zi-Mnk1PxjEIG32HAGILkTOF

Master's level course

- Taken by Bachelor's/Masters/PhD students
- Cutting-edge research topics + fundamentals in Computer Architecture
- 5 Simulator-based Lab Assignments
- Potential research exploration
- Many research readings

<https://www.youtube.com/onurmutlulectures>

RowHammer & DRAM Exploration (Fall 2022)

Fall 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=softmc

Spring 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=softmc

Youtube Livestream (Spring 2022):

- https://www.youtube.com/watch?v=r5QxuoJWttg&list=PL5Q2soXY2Zi_1trfCckr6PTN8WR72icUO

Bachelor's course

- Elective at ETH Zurich
- Introduction to DRAM organization & operation
- Tutorial on using FPGA-based infrastructure
- Verilog & C++
- Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

| Week | Date | Livestream | Meeting | Learning Materials | Assignments |
|------|---------------|------------|---|---|-------------|
| W0 | 23.02 Wed. | | P&S SoftMC Tutorial | SoftMC Tutorial Slides (PDF) (PPT) | |
| W1 | 08.03 Tue. | | M1: Logistics & Intro to DRAM and SoftMC (PDF) (PPT) | Required Materials Recommended Materials | HW0 |
| W2 | 15.03 Tue. | | M2: Revisiting RowHammer (PDF) (PPT) | (Paper PDF) | |
| W3 | 22.03 Tue. | | M3: Uncovering in-DRAM TRR & TRRespass (PDF) (PPT) | | |
| W4 | 29.03 Tue. | | M4: Deeper Look Into RowHammer's Sensitivities (PDF) (PPT) | | |
| W5 | 05.04 Tue. | | M5: QUAC-TRNG (PDF) (PPT) | | |
| W6 | 12.04 Tue. | | M6: PiDRAM (PDF) (PPT) | | |

Exploration of Emerging Memory Systems (Fall 2022)

Fall 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/fall2022/doku.php?id=ramulator

Spring 2022 Edition:

- https://safari.ethz.ch/projects_and_seminars/spring2022/doku.php?id=ramulator

Youtube Livestream (Spring 2022):

- https://www.youtube.com/watch?v=aM-lIXRQd3s&list=PL5Q2soXY2Zi_TlmlGw_Z8hBo2925ZApgV

Bachelor's course

- Elective at ETH Zurich
- Introduction to memory system simulation
- Tutorial on using Ramulator
- C++
- Potential research exploration

<https://www.youtube.com/onurmutlulectures>

Lecture Video Playlist on YouTube

Lecture Playlist



2022 Meetings/Schedule (Tentative)

| Week | Date | Livestream | Meeting | Learning Materials | Assignments |
|------|------------|---|--|--------------------|-------------|
| W1 | 09.03 Wed. | YouTube Video | M1: Logistics & Intro to Simulating Memory Systems Using Ramulator PDF (PDF) PPT (PPT) | | HW0 |
| W2 | 16.03 Fri. | YouTube Video | M2: Tutorial on Using Ramulator PDF (PDF) PPT (PPT) | | |
| W3 | 25.02 Fri. | YouTube Video | M3: BlockHammer PDF (PDF) PPT (PPT) | | |
| W4 | 01.04 Fri. | YouTube Video | M4: CLR-DRAM PDF (PDF) PPT (PPT) | | |
| W5 | 08.04 Fri. | YouTube Video | M5: SIMDRAM PDF (PDF) PPT (PPT) | | |
| W6 | 29.04 Fri. | YouTube Video | M6: DAMOV PDF (PDF) PPT (PPT) | | |
| W7 | 06.05 Fri. | YouTube Video | M7: Synchron PDF (PDF) PPT (PPT) | | |

An Early Proposal for Intelligent Controllers [IMW'13]

- Onur Mutlu,
"Memory Scaling: A Systems Architecture Perspective"
*Proceedings of the 5th International Memory Workshop (**IMW**), Monterey, CA, May 2013. Slides
(pptx) (pdf)
EETimes Reprint*

Memory Scaling: A Systems Architecture Perspective

Onur Mutlu
Carnegie Mellon University
onur@cmu.edu
<http://users.ece.cmu.edu/~omutlu/>

Industry Is Writing Papers About It, Too

DRAM Process Scaling Challenges

❖ Refresh

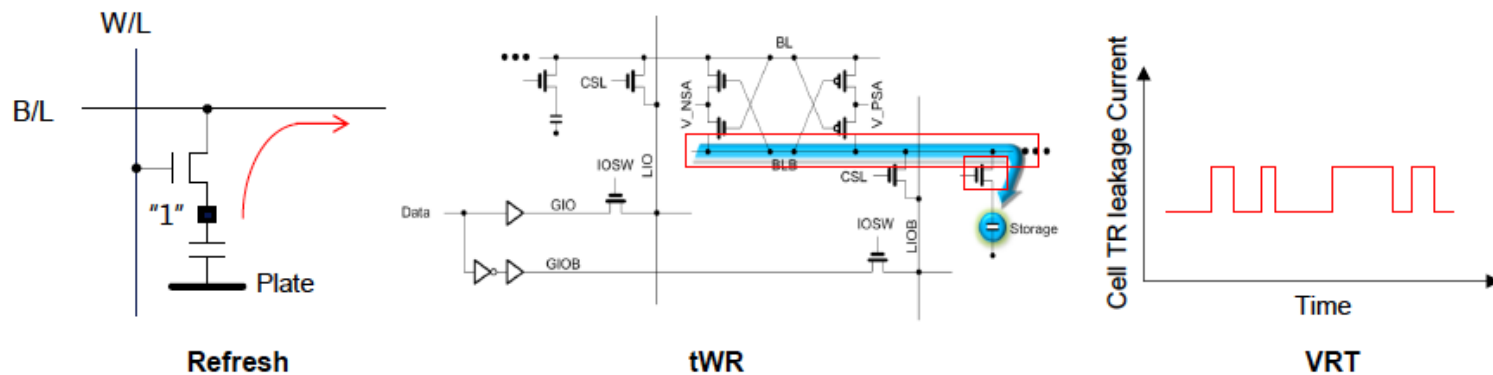
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance
- Leakage current of cell access transistors increasing

❖ tWR

- Contact resistance between the cell capacitor and access transistor increasing
- On-current of the cell access transistor decreasing
- Bit-line resistance increasing

❖ VRT

- Occurring more frequently with cell capacitance decreasing



Industry Is Writing Papers About It, Too

DRAM Process Scaling Challenges

❖ Refresh

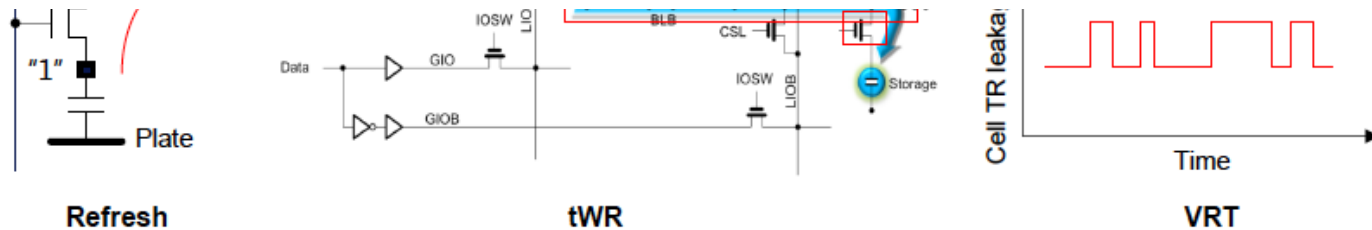
- Difficult to build high-aspect ratio cell capacitors decreasing cell capacitance

THE MEMORY FORUM 2014

Co-Architecting Controllers and DRAM to Enhance DRAM Process Scaling

Uksong Kang, Hak-soo Yu, Churoo Park, *Hongzhong Zheng,
**John Halbert, **Kuljit Bains, SeongJin Jang, and Joo Sun Choi

*Samsung Electronics, Hwasung, Korea / *Samsung Electronics, San Jose / **Intel*



Final Thoughts on RowHammer

Aside: Byzantine Failures

- This class of failures is known as **Byzantine failures**
- Characterized by
 - **Undetected erroneous computation**
 - Opposite of “fail fast (with an error or no result)”
- “erroneous” can be “malicious” (intent is the only distinction)
- Very difficult to detect and confine Byzantine failures
- **Do all you can to avoid them**
- Lamport et al., “The Byzantine Generals Problem,” ACM TOPLAS 1982.

Aside: Byzantine Generals Problem

The Byzantine Generals Problem

LESLIE LAMPORT, ROBERT SHOSTAK, and MARSHALL PEASE

SRI International

Reliable computer systems must handle malfunctioning components that give conflicting information to different parts of the system. This situation can be expressed abstractly in terms of a group of generals of the Byzantine army camped with their troops around an enemy city. Communicating only by messenger, the generals must agree upon a common battle plan. However, one or more of them may be traitors who will try to confuse the others. The problem is to find an algorithm to ensure that the loyal generals will reach agreement. It is shown that, using only oral messages, this problem is solvable if and only if more than two-thirds of the generals are loyal; so a single traitor can confound two loyal generals. With unforgeable written messages, the problem is solvable for any number of generals and possible traitors. Applications of the solutions to reliable computer systems are then discussed.

Categories and Subject Descriptors: C.2.4. [**Computer-Communication Networks**]: Distributed Systems—*network operating systems*; D.4.4 [**Operating Systems**]: Communications Management—*network communication*; D.4.5 [**Operating Systems**]: Reliability—*fault tolerance*

General Terms: Algorithms, Reliability

Additional Key Words and Phrases: Interactive consistency

ACM TOPLAS 1982

Funding Acknowledgments

- Alibaba, AMD, [ASML](#), [Google](#), [Facebook](#), [Hi-Silicon](#), HP Labs, [Huawei](#), IBM, [Intel](#), [Microsoft](#), Nvidia, Oracle, Qualcomm, Rambus, Samsung, Seagate, [VMware](#), [Xilinx](#)
- [Microsoft Swiss JRC](#)
- NSF
- NIH
- GSRC
- [SRC](#)
- CyLab
- [EFCL](#)

Thank you!

First RowHammer Analysis [ISCA 2014]

- Yoongu Kim, Ross Daly, Jeremie Kim, Chris Fallin, Ji Hye Lee, Donghyuk Lee, Chris Wilkerson, Konrad Lai, and Onur Mutlu,
"Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors"
Proceedings of the 41st International Symposium on Computer Architecture (ISCA), Minneapolis, MN, June 2014.
[\[Slides \(pptx\) \(pdf\)\]](#) [\[Lightning Session Slides \(pptx\) \(pdf\)\]](#) [\[Source Code and Data\]](#) [\[Lecture Video\]](#) (1 hr 49 mins), 25 September 2020]
One of the 7 papers of 2012-2017 selected as Top Picks in Hardware and Embedded Security for IEEE TCAD ([link](#)).
Selected to the ISCA-50 25-Year Retrospective Issue covering 1996-2020 in 2023 ([Retrospective \(pdf\)](#) [Full Issue](#)).

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Yoongu Kim¹ Ross Daly* Jeremie Kim¹ Chris Fallin* Ji Hye Lee¹
Donghyuk Lee¹ Chris Wilkerson² Konrad Lai Onur Mutlu¹

¹Carnegie Mellon University ²Intel Labs

Retrospective on RowHammer & Future

- Onur Mutlu,
"The RowHammer Problem and Other Issues We May Face as Memory Becomes Denser"

*Invited Paper in Proceedings of the Design, Automation, and Test in Europe Conference (**DATE**), Lausanne, Switzerland, March 2017.*

[Slides (pptx) (pdf)]

The RowHammer Problem and Other Issues We May Face as Memory Becomes Denser

Onur Mutlu
ETH Zürich
onur.mutlu@inf.ethz.ch
<https://people.inf.ethz.ch/omutlu>

A More Recent RowHammer Retrospective

- Onur Mutlu and Jeremie Kim,
["RowHammer: A Retrospective"](#)
IEEE Transactions on Computer-Aided Design of Integrated Circuits and Systems (TCAD) Special Issue on Top Picks in Hardware and Embedded Security, 2019.
[[Preliminary arXiv version](#)]
[[Slides from COSADE 2019 \(pptx\)](#)]
[[Slides from VLSI-SOC 2020 \(pptx\) \(pdf\)](#)]
[[Talk Video](#) (1 hr 15 minutes, with Q&A)]

RowHammer: A Retrospective

Onur Mutlu^{§‡} Jeremie S. Kim^{‡§}
§ETH Zürich ‡Carnegie Mellon University

A RowHammer Survey: Recent Update

- Onur Mutlu, Ataberk Olgun, and A. Giray Yaglikci,
"Fundamentally Understanding and Solving RowHammer"
Invited Special Session Paper at the 28th Asia and South Pacific Design Automation Conference (ASP-DAC), Tokyo, Japan, January 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#) ([pdf](#))]
[[Talk Video](#) (26 minutes)]

Fundamentally Understanding and Solving RowHammer

Onur Mutlu
onur.mutlu@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

Ataberk Olgun
ataberk.olgund@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

A. Giray Yağlıkçı
giray.yaglikci@safari.ethz.ch
ETH Zürich
Zürich, Switzerland

<https://arxiv.org/pdf/2211.07613.pdf>

RowHammer & RowPress on HBM Chips

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun Majd Osseiran

A. Giray Yağlıkçı Yahya Can Tuğrul Haocong Luo Steve Rhyner

Behzad Salami Juan Gomez Luna Onur Mutlu

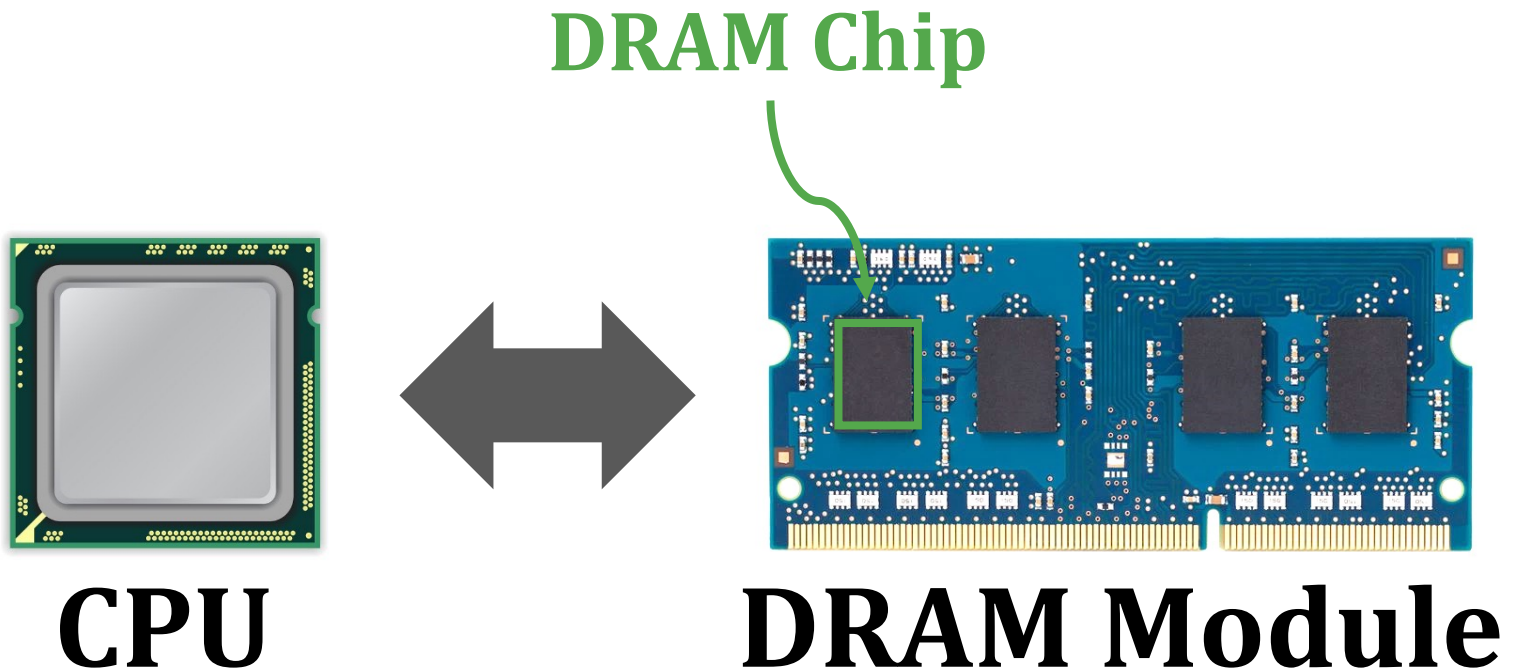
SAFARI

ETH zürich

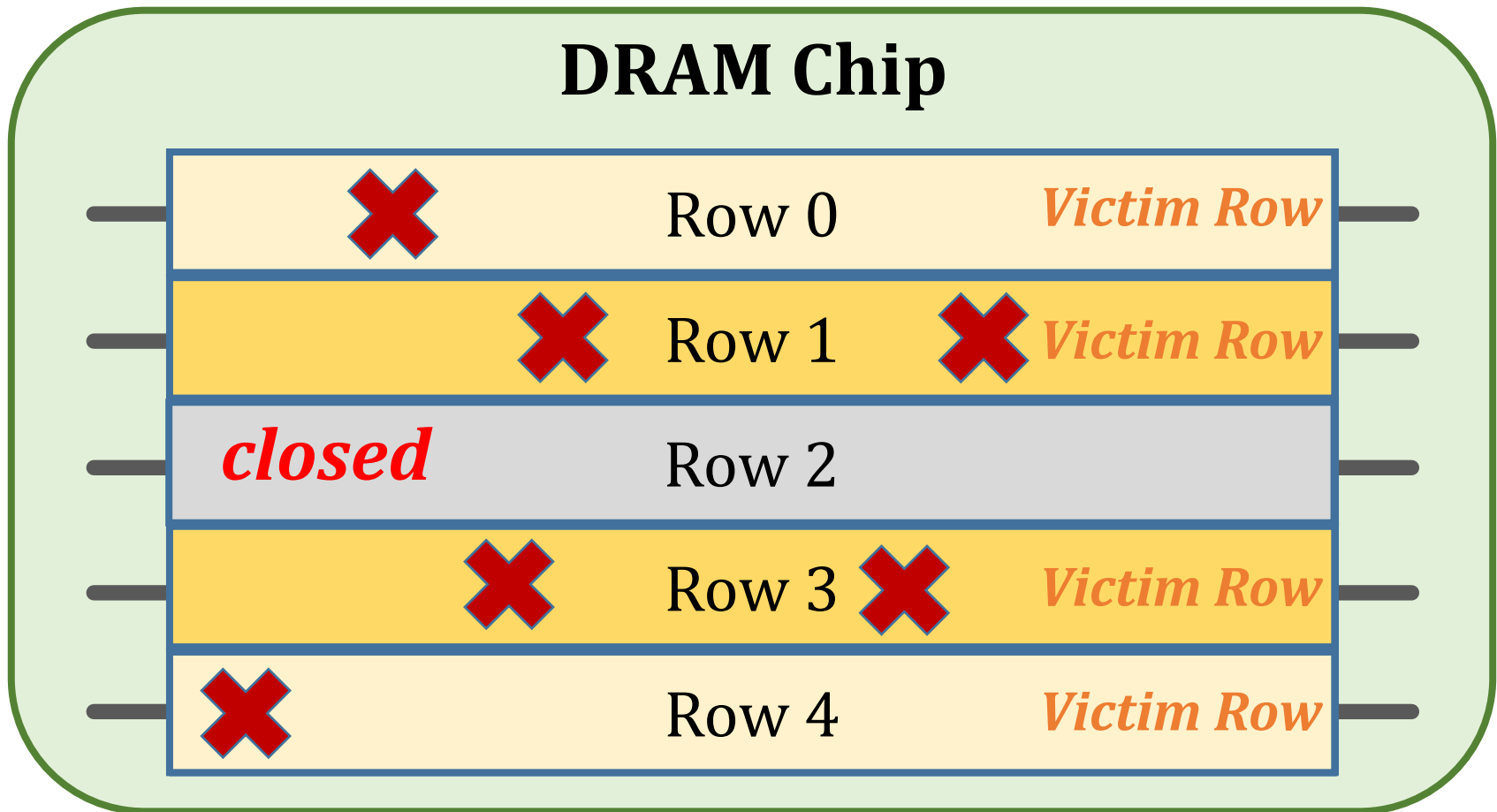


AMERICAN
UNIVERSITY
OF BEIRUT

The RowHammer Vulnerability (I)

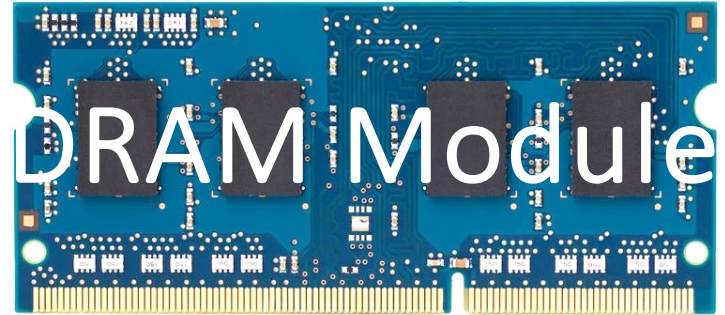
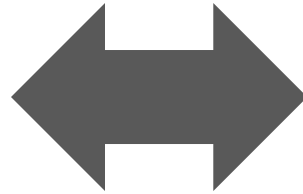


The RowHammer Vulnerability (II)

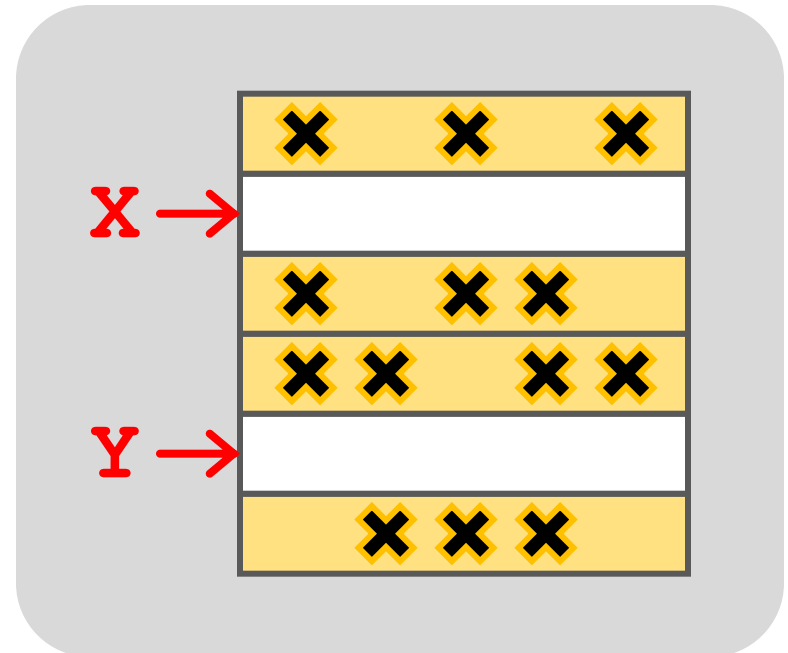


Repeatedly **opening** (activating) and **closing** (precharging) a DRAM row causes **RowHammer bit flips** in nearby rows

A Simple Program Can Induce Bitflips



```
loop:  
  mov  (X),  %eax  
  mov  (Y),  %ebx  
  clflush (X)  
  clflush (Y)  
  mfence  
  jmp  loop
```



One Can Take Over a System

Flipping Bits in Memory Without Accessing Them: An Experimental Study of DRAM Disturbance Errors

Abstract. **Memory isolation** is a key property of a reliable and secure computing system — an access to one memory address should not have unintended side effects on data stored in other addresses. However, as DRAM process technology

Project Zero

[Flipping Bits in Memory Without Accessing Them:
An Experimental Study of DRAM Disturbance Errors](#)
(Kim et al., ISCA 2014)

News and updates from the Project Zero team at Google

Monday, March 9, 2015

[Exploiting the DRAM rowhammer bug to
gain kernel privileges](#) (Seaborn, 2015)

Exploiting the DRAM rowhammer bug to gain kernel privileges

Most DRAM Modules Are Vulnerable (2020)

| DRAM type-node | Number of Chips (Modules) Tested | | | |
|-------------------|----------------------------------|---------------|---------------|--------------|
| | <i>Mfr. A</i> | <i>Mfr. B</i> | <i>Mfr. C</i> | <i>Total</i> |
| DDR3-old | 56 (10) | 88 (11) | 28 (7) | 172 (28) |
| DDR3-new | 80 (10) | 52 (9) | 104 (13) | 236 (32) |
| DDR4-old | 112 (16) | 24 (3) | 128 (18) | 264 (37) |
| DDR4-new | 264 (43) | 16 (2) | 108 (28) | 388 (73) |
| LPDDR4-1x | 12 (3) | 180 (45) | N/A | 192 (48) |
| LPDDR4-1y | 184 (46) | N/A | 144 (36) | 328 (82) |

All tested DRAM types are susceptible to RowHammer bitflips

What about High Bandwidth Memory (HBM)?

Executive Summary

Motivation: HBM chips have new architectural characteristics (e.g., 3D-stacked dies) that might affect the RowHammer vulnerability in various ways

Understanding RowHammer enables designing effective and efficient solutions

Problem: No prior study demonstrates the RowHammer vulnerability in HBM

Goal: Experimentally analyze how vulnerable HBM DRAM chips are to RowHammer

Experimental Study: Detailed experimental characterization of RowHammer in a modern HBM2 DRAM chip. Our study provides two main findings:

1. Spatial variation of RowHammer vulnerability

- Different channels in a 3D-stacked HBM chip exhibit different RowHammer vulnerability
- DRAM rows near the end of a DRAM bank are more RowHammer resilient

2. On-DRAM-die RowHammer mitigations

- A modern HBM chip implements undisclosed on-DRAM-die RowHammer mitigation
- The mitigation refreshes a victim row after every 17 periodic refresh operations (e.g., similar to DDR4 chips)

Outline

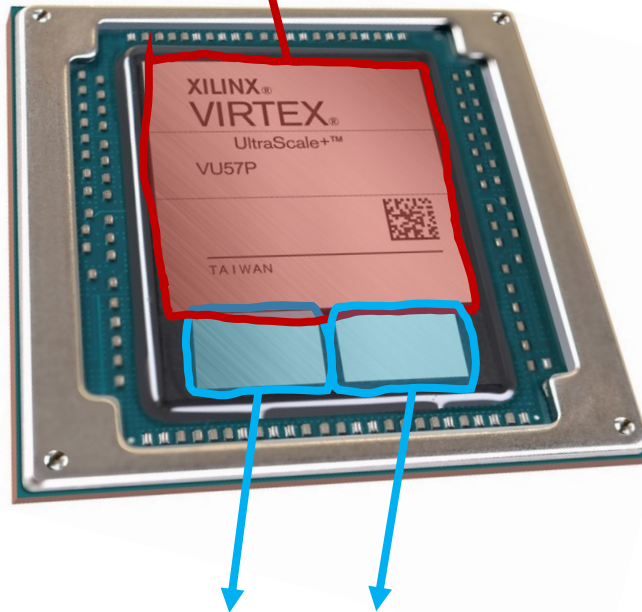
1. HBM DRAM Organization & Operation
2. DRAM Cell Leakage & RowHammer
3. HBM DRAM Testing Methodology
4. RowHammer Spatial Variation Analysis
5. On-die RowHammer Mitigation Analysis
6. Conclusion

Outline

1. HBM DRAM Organization & Operation
2. DRAM Cell Leakage & RowHammer
3. HBM DRAM Testing Methodology
4. RowHammer Spatial Variation Analysis
5. On-die RowHammer Mitigation Analysis
6. Conclusion

System with High Bandwidth Memory

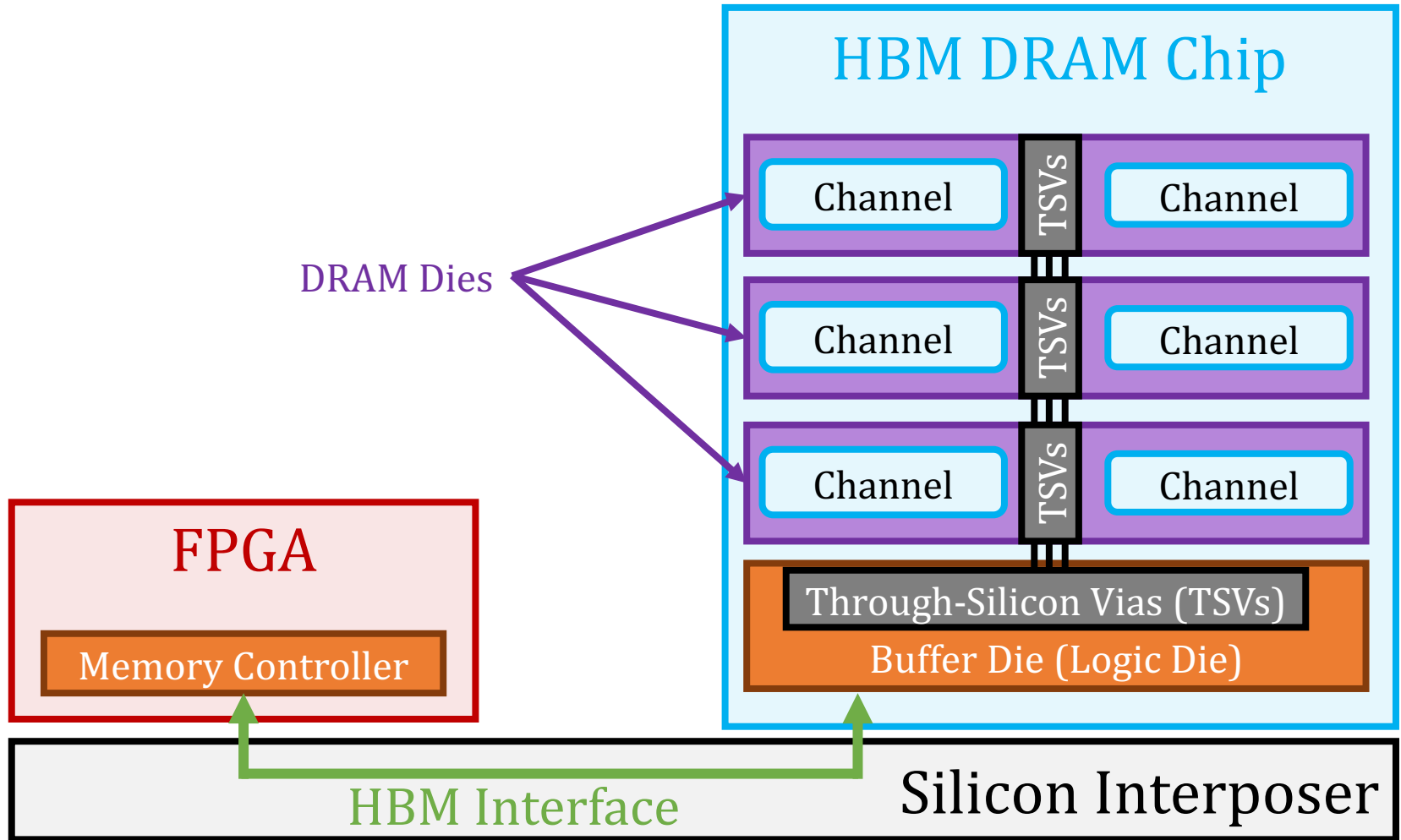
Compute Chip (e.g., FPGA)



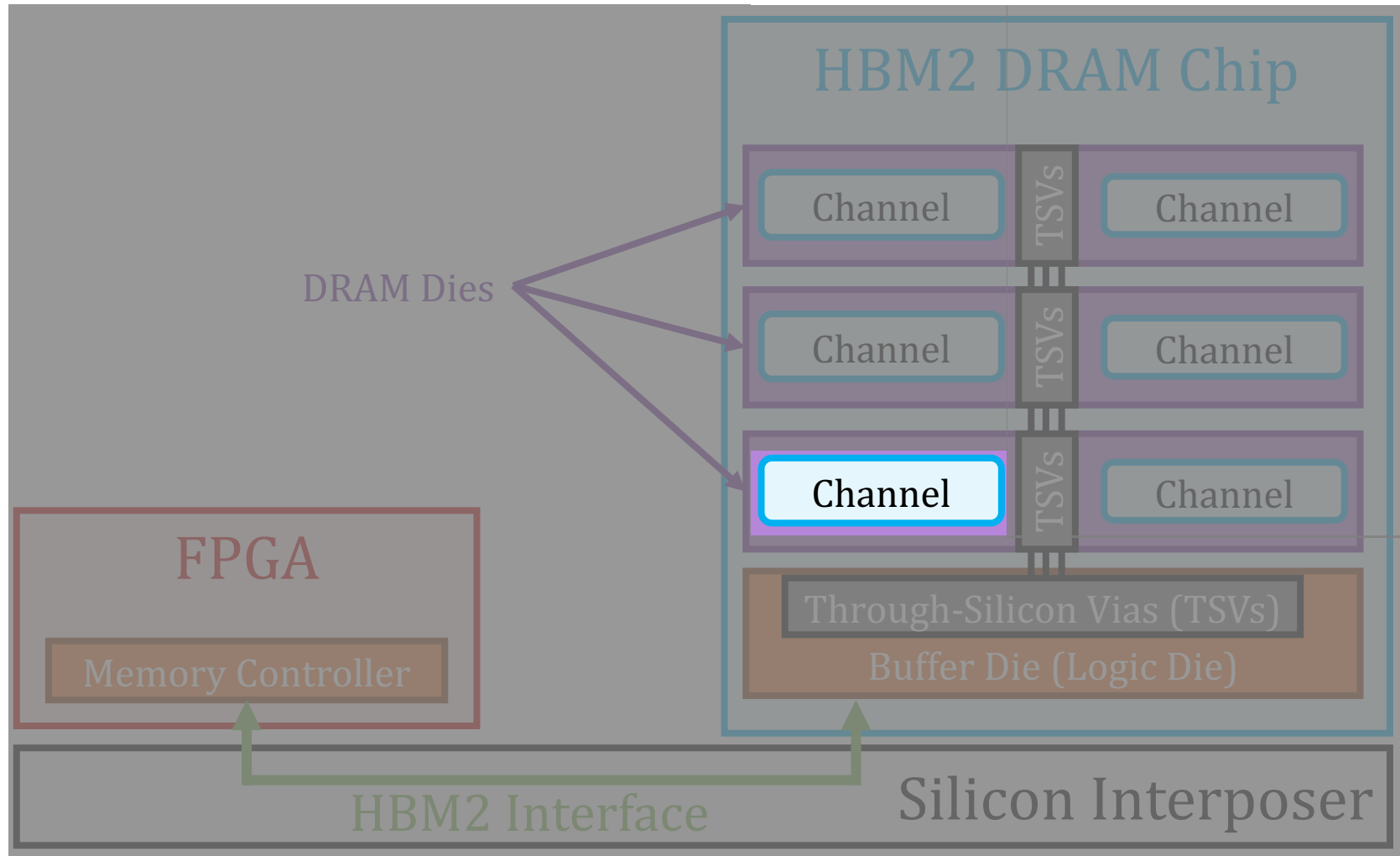
Memory Chip
(e.g., HBM DRAM)

Inside one **package**

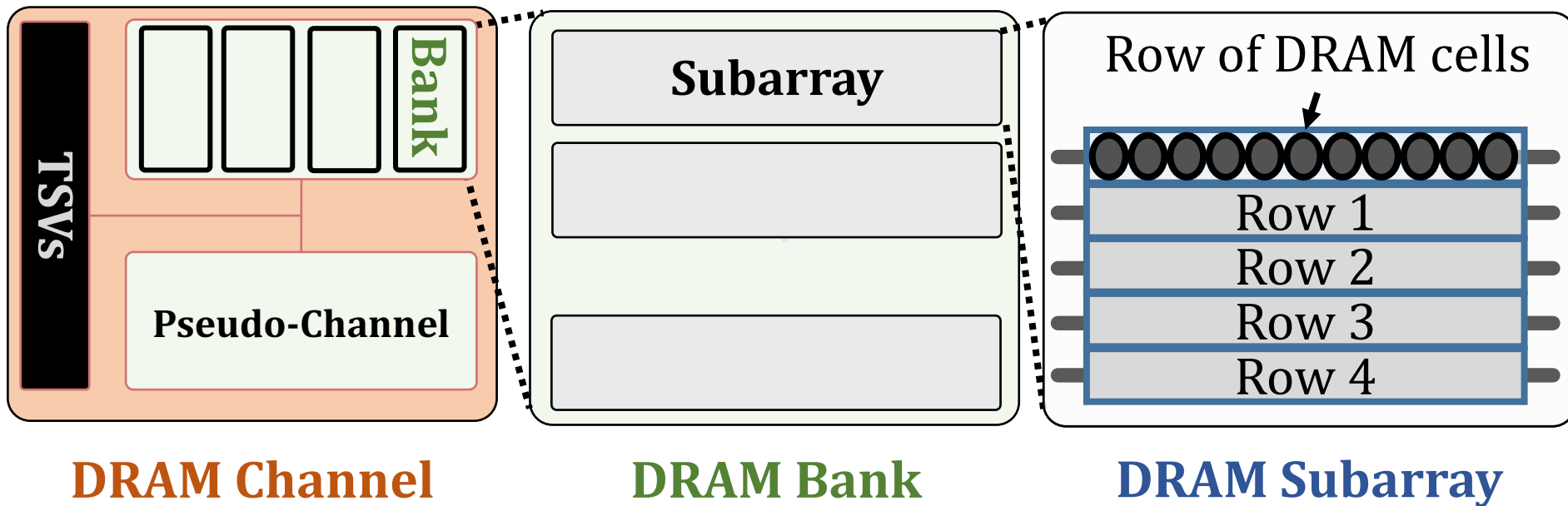
HBM DRAM Organization (I)



HBM DRAM Organization (I)



HBM DRAM Organization (II)



Outline

1. HBM DRAM Organization & Operation

2. DRAM Cell Leakage & RowHammer

3. HBM DRAM Testing Methodology

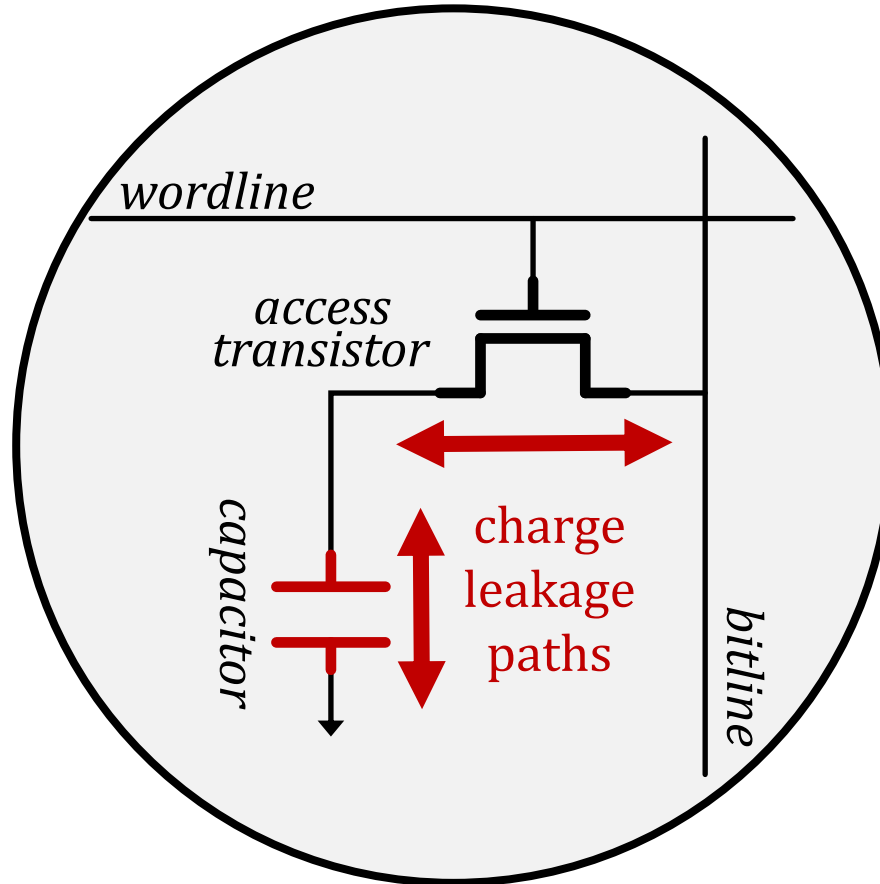
4. RowHammer Spatial Variation Analysis

5. On-die RowHammer Mitigation Analysis

6. Conclusion

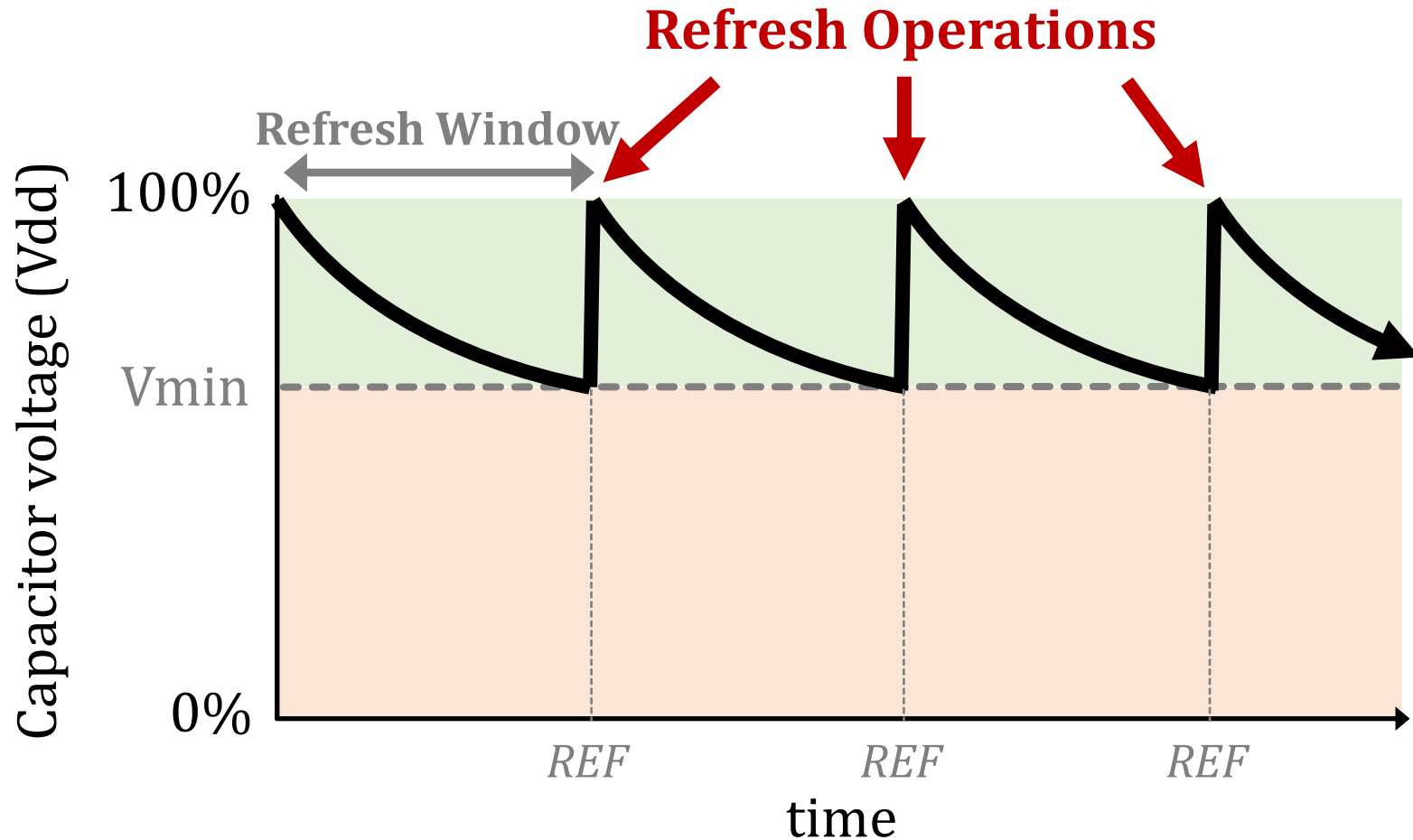
DRAM Cell Leakage

Each cell encodes information in **leaky** capacitors



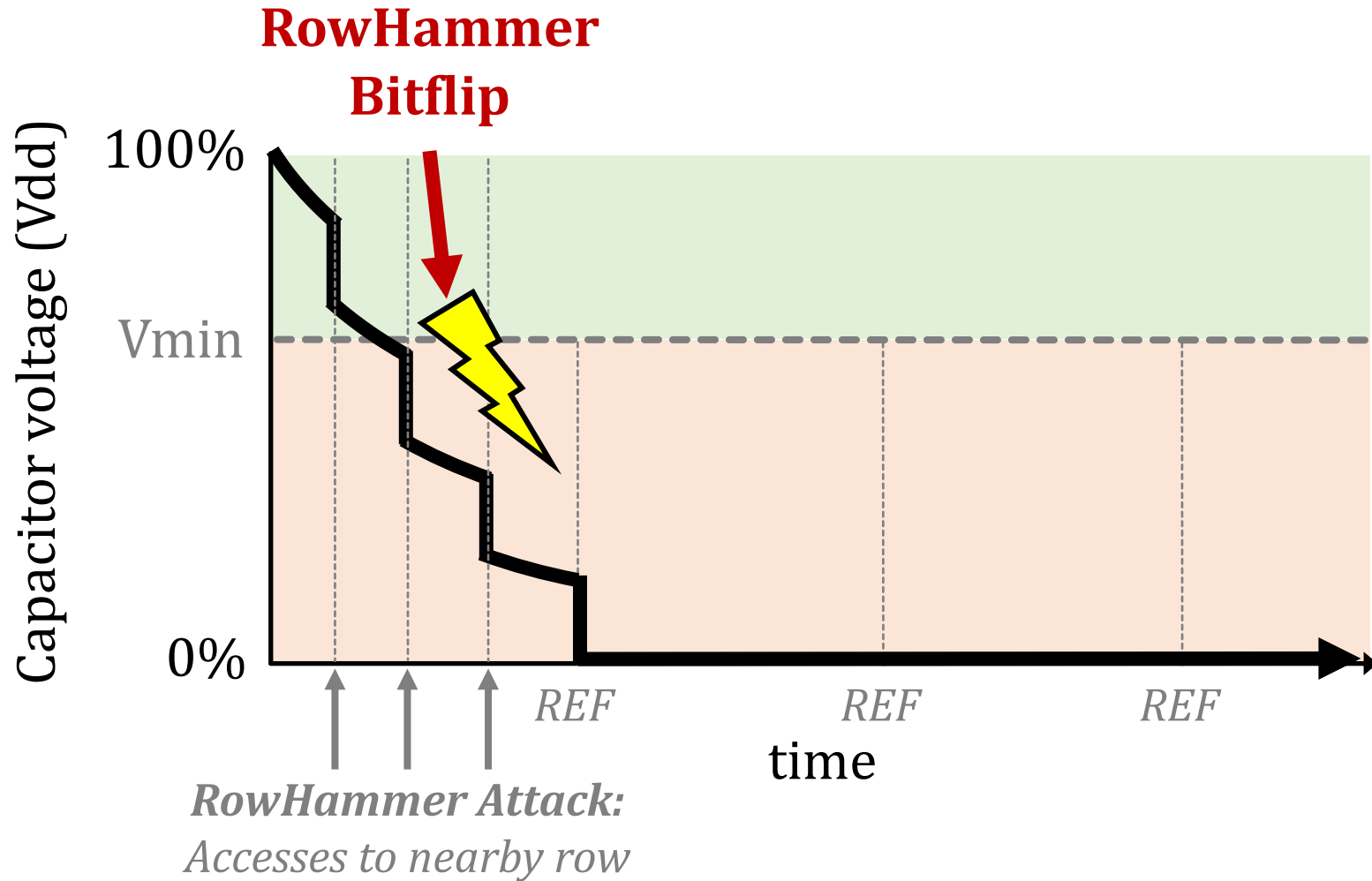
Stored data is **corrupted** if too much charge leaks (i.e., the capacitor voltage degrades too much)

DRAM Refresh



Periodic **refresh operations** preserve stored data

RowHammer Bitflips



Problem & Goal

Problem

No **prior study** demonstrates the **RowHammer** vulnerability in **high bandwidth memory**

Our Goal

Experimentally analyze how vulnerable **real** high bandwidth memory chips are to RowHammer

Outline

1. HBM DRAM Organization & Operation

2. DRAM Cell Leakage & RowHammer

3. HBM DRAM Testing Methodology

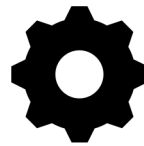
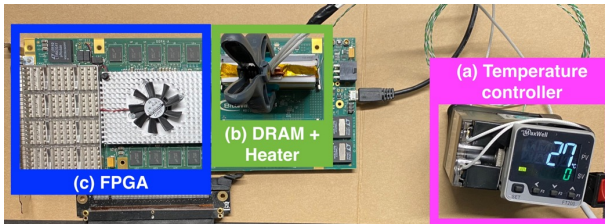
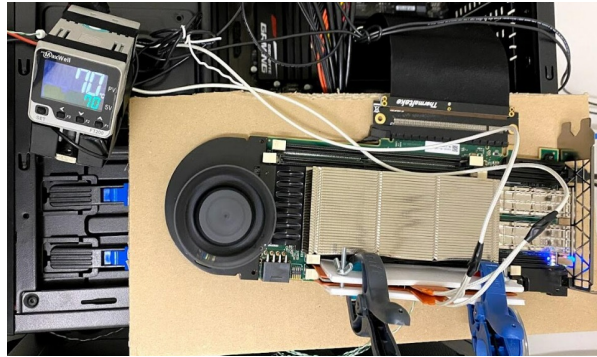
4. RowHammer Spatial Variation Analysis

5. On-die RowHammer Mitigation Analysis

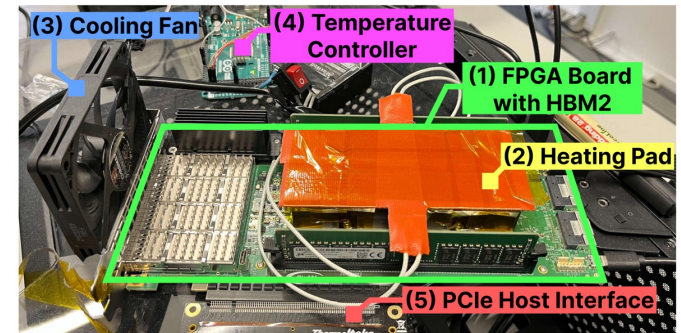
6. Conclusion

DRAM Testing Infrastructure

DRAM Bender DDR3/4 Testing Infrastructure



Adapt to work
with HBM2 chips



<https://github.com/CMU-SAFARI/DRAM-Bender>



CMU-SAFARI / DRAM-Bender

<> Code

Issues 1

Pull requests 1



DRAM-Bender

Public

About

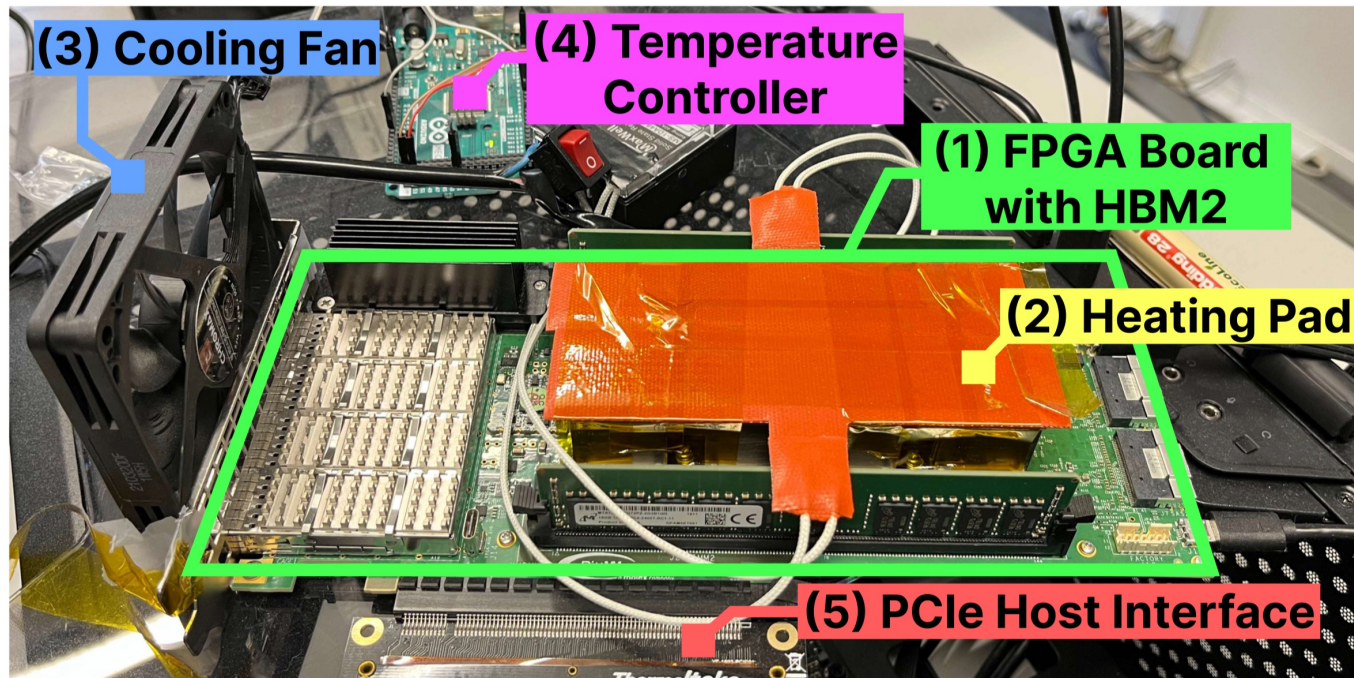


DRAM Bender is the first open source DRAM testing infrastructure that can be used to easily and comprehensively test state-of-the-art DDR4 modules of different form factors. Five prototypes are available on different FPGA boards.

Olgun et al., "[DRAM Bender: An Extensible and Versatile FPGA-based Infrastructure to Easily Test State-of-the-art DRAM Chips](#)," in TCAD, 2023.

DRAM Testing Infrastructure

FPGA-based HBM2 Testing Setup (Bittware XUPV VH)



Fine-grained control over **DRAM commands,**
timing parameters ($\pm 1.66\text{ns}$)

RowHammer Testing Methodology (I)

To characterize our DRAM chips at **worst-case** conditions:

1. Prevent sources of interference during core test loop

- **No DRAM refresh**: to avoid refreshing victim row
- **No RowHammer mitigation mechanisms**: to observe circuit-level effects
- Test for **less than a refresh window (32ms)** to avoid retention failures
- **Repeat tests** for five times

2. Worst-case RowHammer access sequence

- We use **worst-case** RowHammer access sequence based on prior works' observations
- Double-sided RowHammer: **repeatedly access the two physically-adjacent rows as fast as possible**



Record bitflips
in victim



RowHammer Testing Methodology (II)

- Tested HBM2 chip's organization:

- 8 channels
- 2 pseudo-channels
- 16 banks
- 16384 rows (1 KiB each)



Xilinx FPGA
with HBM2 DRAM chips

- Test **all** channels, pseudo-channels, banks
- Test **first, middle, and last 3K** rows in a bank
 - 9K out of 16K (more than half)
- Keep HBM2 chip temperature at **85°C**

Metrics

1. Bit error rate (BER):

The fraction of DRAM cells in a row that experience a bitflip after 512K activations

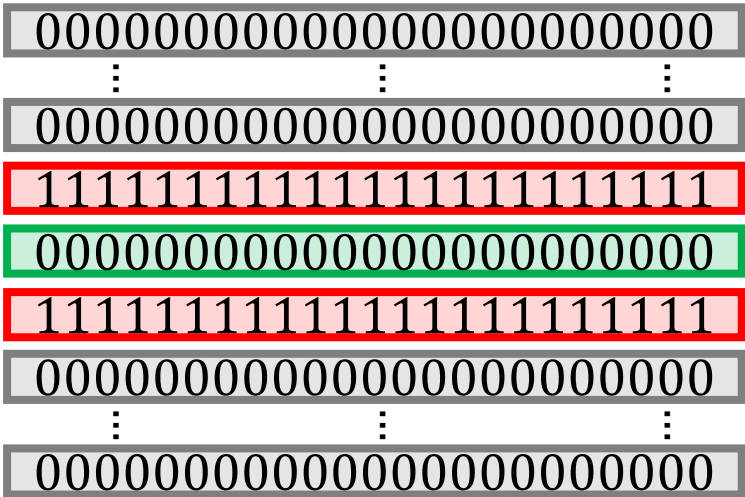
Higher is worse

2. Hammer Count for the First Bitflip (HC_{first}):

Aggressor row activation count to cause the first bitflip in the victim row

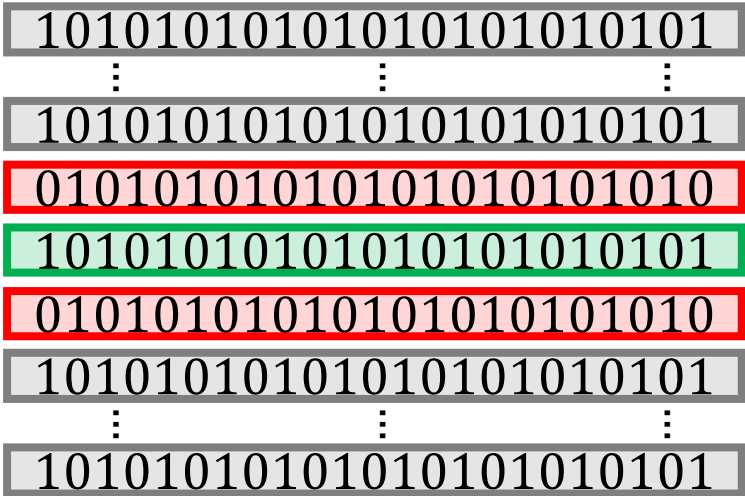
Lower is worse

Tested Data Patterns



| Row Addresses | Rowstripe0 | Rowstripe1 | Checker0 | Checker1 |
|--------------------------|------------|------------|----------|----------|
| Victim (V) | 0x00 | 0xFF | 0x55 | 0xAA |
| Aggressors ($V \pm 1$) | 0xFF | 0x00 | 0xAA | 0x55 |
| $V \pm [2:8]$ | 0x00 | 0xFF | 0x55 | 0xAA |

Tested Data Patterns



| Row Addresses | Rowstripe0 | Rowstripe1 | Checkered0 | Checkered1 |
|--------------------|------------|------------|------------|------------|
| Victim (V) | 0x00 | 0xFF | 0x55 | 0xAA |
| Aggressors (V ± 1) | 0xFF | 0x00 | 0xAA | 0x55 |
| V ± [2:8] | 0x00 | 0xFF | 0x55 | 0xAA |

Tested Data Patterns



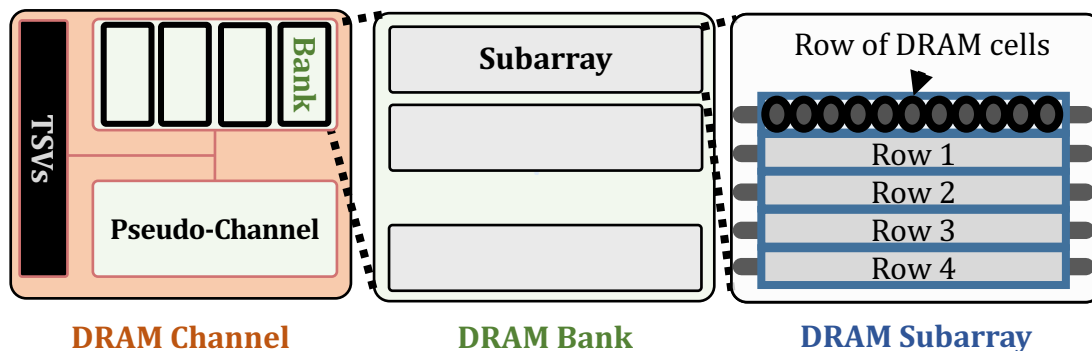
| Row Addresses | Rowstripe0 | Rowstripe1 | Checkered0 | Checkered1 |
|--------------------------|------------|------------|------------|------------|
| Victim (V) | 0x00 | 0xFF | 0x55 | 0xAA |
| Aggressors ($V \pm 1$) | 0xFF | 0x00 | 0xAA | 0x55 |
| $V \pm [2:8]$ | 0x00 | 0xFF | 0x55 | 0xAA |

Worst-case data pattern (**WCDP**) of a row: Causes smallest HC_{first} for a row

Two Main Analyses

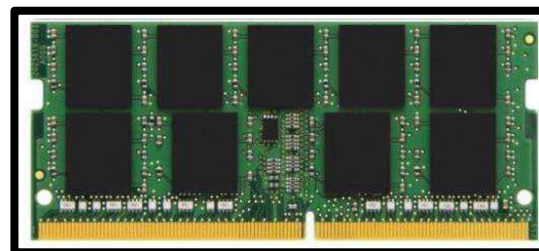
1. Spatial variation of RowHammer vulnerability

How does the RowHammer vulnerability change across **channels, pseudo-channels, banks, rows** in HBM?



2. On-DRAM-die RowHammer mitigations

Do real HBM chips implement **undisclosed RowHammer mitigations** resembling those that exist in DDR4?



Outline

1. HBM DRAM Organization & Operation

2. DRAM Cell Leakage & RowHammer

3. HBM DRAM Testing Methodology

4. RowHammer Spatial Variation Analysis

5. On-die RowHammer Mitigation Analysis

6. Conclusion

Key Takeaways from Spatial Variation Analysis

Takeaway 1

Different 3D-stacked HBM2 channels exhibit different RowHammer vulnerability

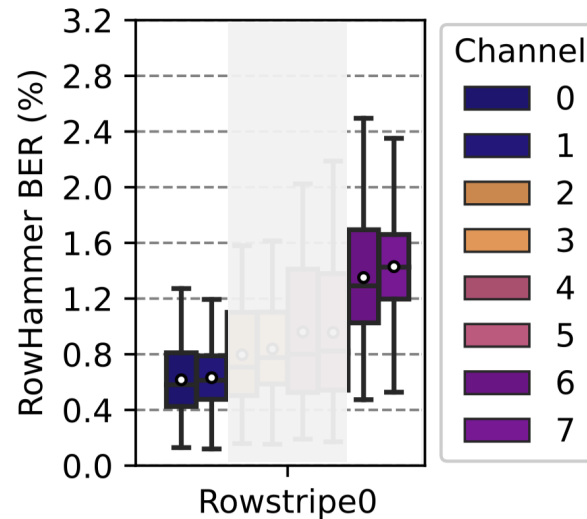
Takeaway 2

DRAM rows near the end of a DRAM bank experience smaller bit error rate (BER) than others

Takeaway 3

Activation count needed to induce the first RowHammer bitflip (HC_{first}) changes with the data pattern and the physical location of the DRAM row

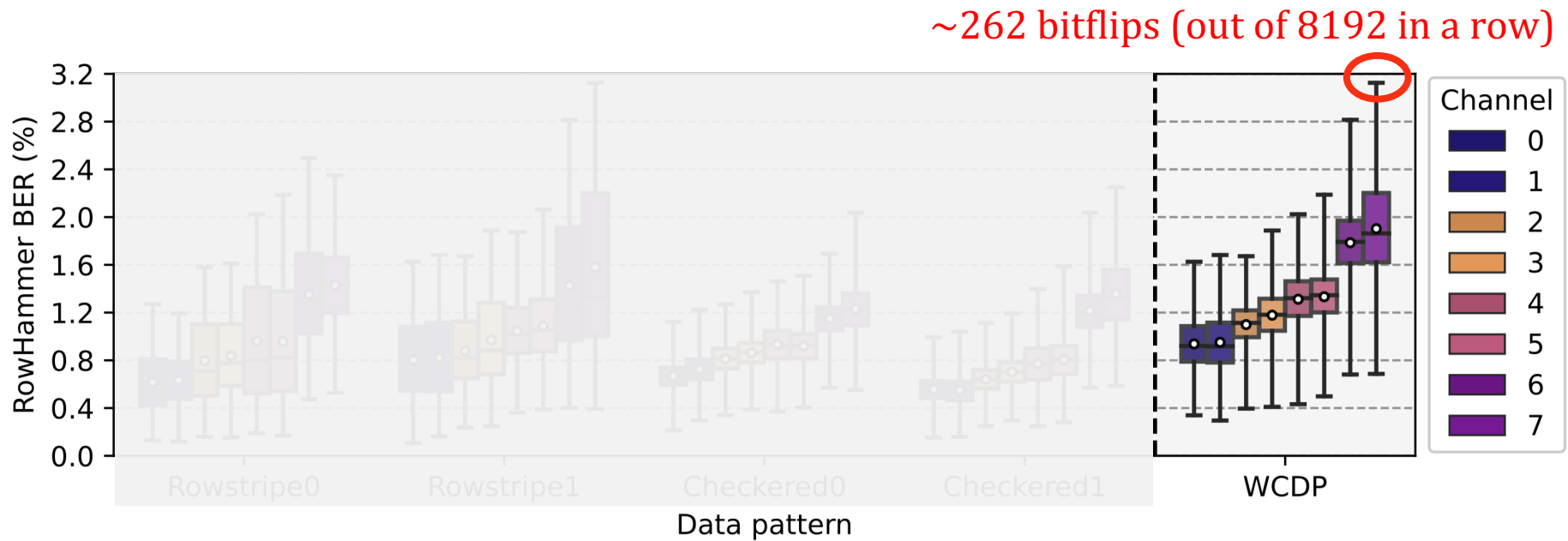
Spatial Distribution of BER (I)



There are **bitflips** in **every** tested DRAM **row**
across **all** tested HBM2 **channels**

BER **varies across channels**:
groups of two channels have different BERs

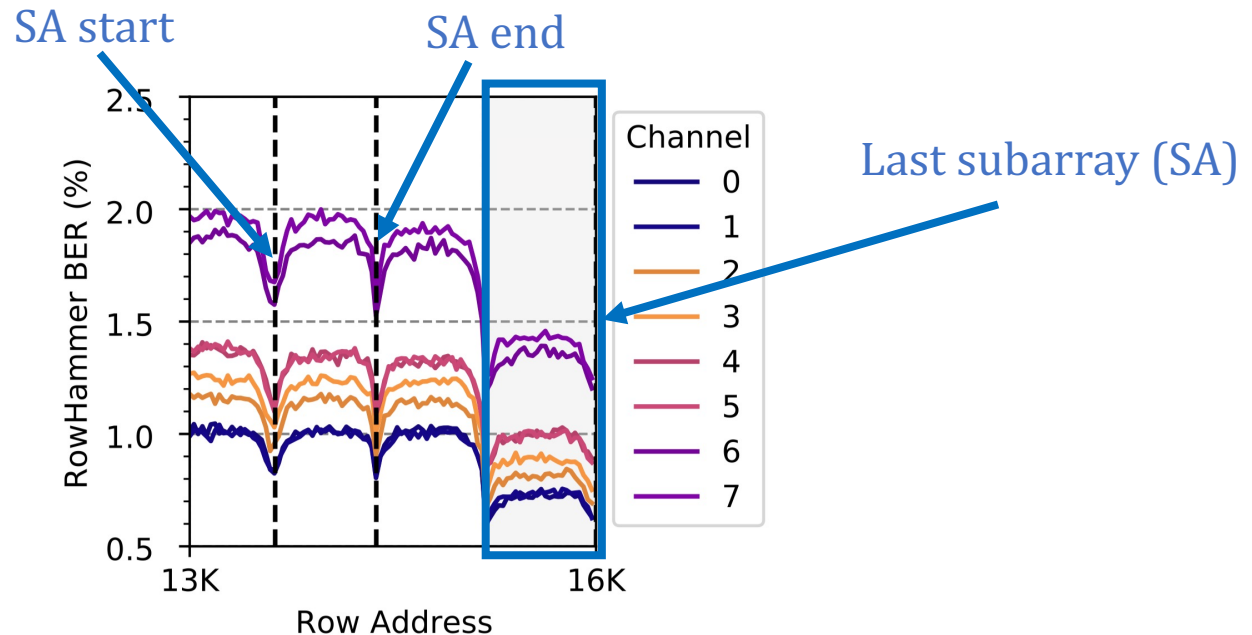
Spatial Distribution of BER (I)



The **data pattern affects** the BER distribution

Up to ~262 bitflips in a row of 8K bits
with 512K aggressor row activations

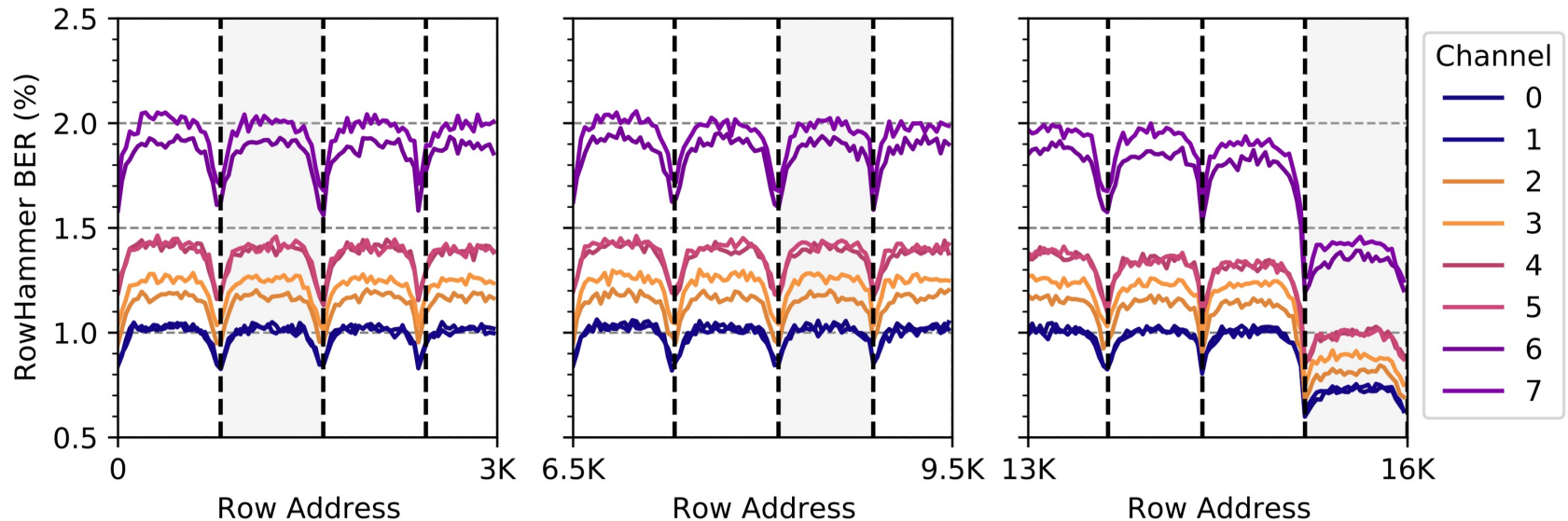
Spatial Distribution of BER (II)



BER is substantially smaller in the **last subarray (i.e., last 832 rows)**

BER periodically increases and decreases across rows:
BER is **higher** in the **middle of a subarray**

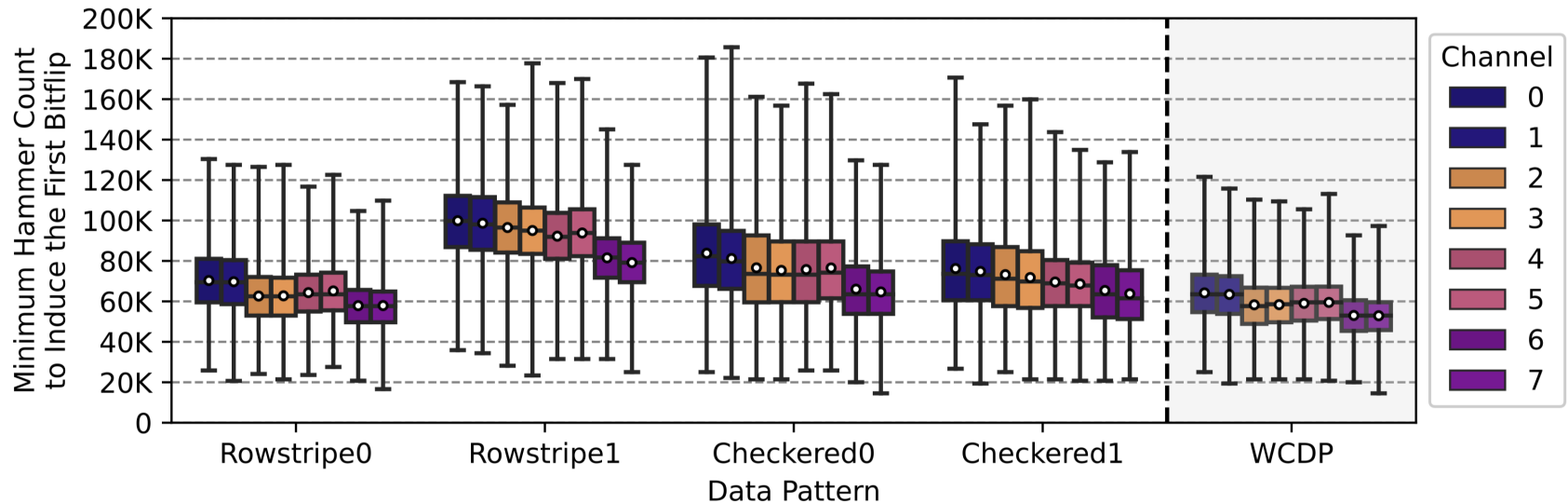
Spatial Distribution of BER (II)



BER is substantially smaller in the **last subarray (i.e., last 832 rows)**

BER periodically increases and decreases across rows:
BER is **higher** in the **middle of a subarray**

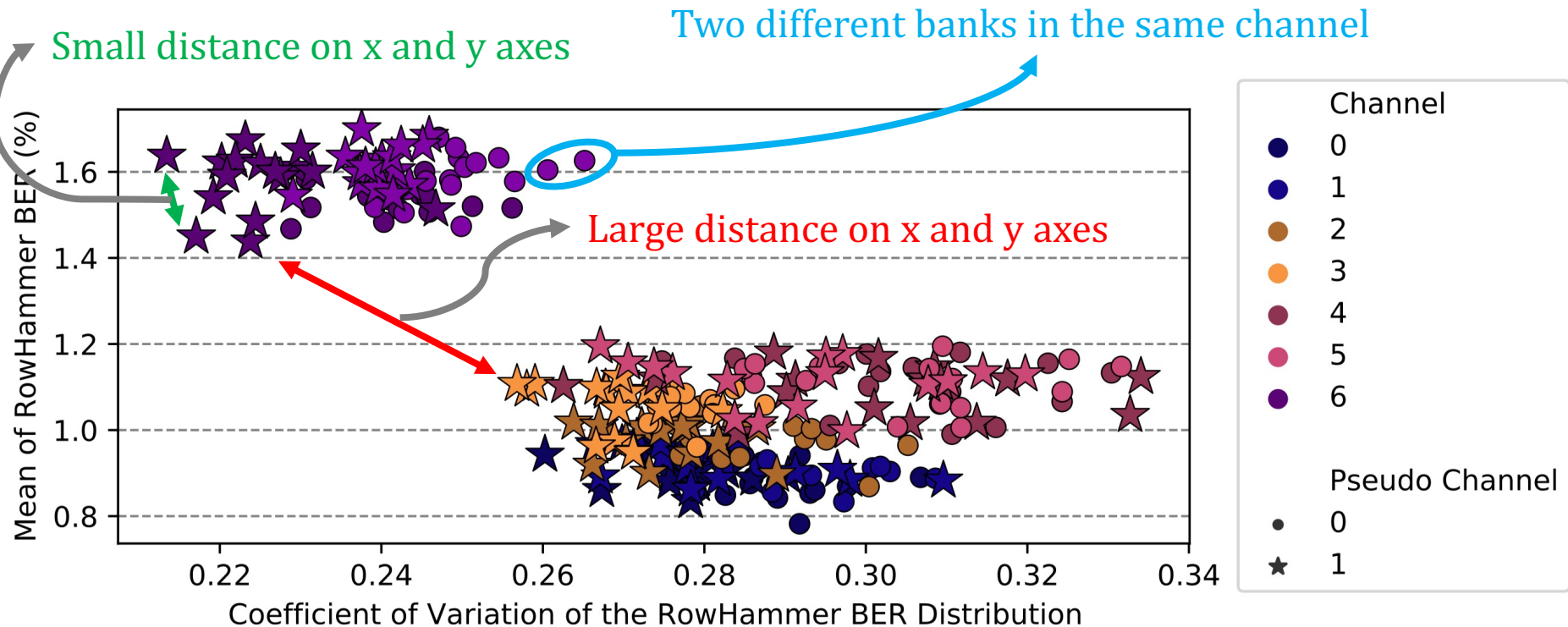
Spatial Distribution of HC_{first}



HC_{first} is as low as **14531** across all tested rows/channels:
Only ~1.3 ms to induce a RowHammer bitflip

HC_{first} distribution heavily **depends on the data pattern**

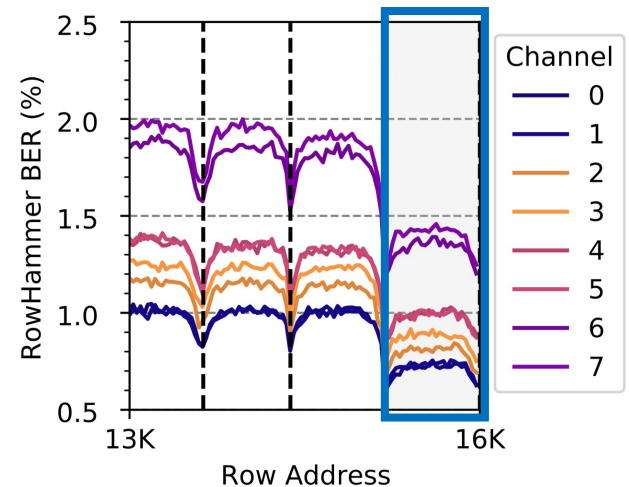
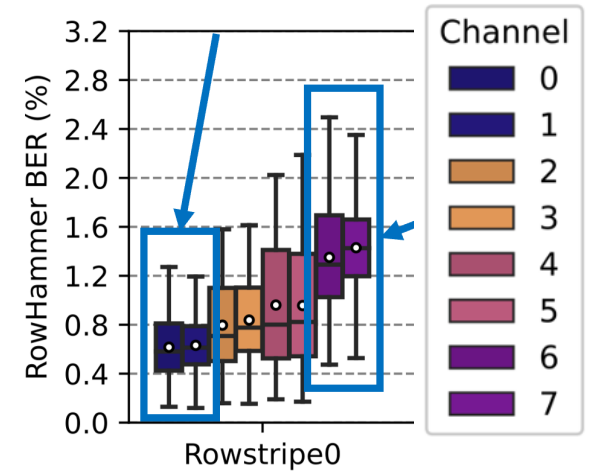
Variation in Bit Error Rate



Banks in the same channel have similar variation in BER

Hypotheses from Characterization

1. Similar BER & HC_{first} within groups of two channels suggests these channels share DRAM dies
2. RowHammer BER changes with the row's proximity to sense amplifiers and bank I/O



Implications on Attacks and Mitigations

Key Observation: RowHammer BER and HC_{first} vary across channels

Two implications for RowHammer attacks and mitigations

A RowHammer attack can use the most-RH-vulnerable HBM2 channel to prepare for and perform the attack faster

A RowHammer mitigation can allocate fewer resources for RowHammer-resilient channels and more efficiently prevent RowHammer bitflips

Outline

1. HBM DRAM Organization & Operation

2. DRAM Cell Leakage & RowHammer

3. HBM DRAM Testing Methodology

4. RowHammer Spatial Variation Analysis

5. On-die RowHammer Mitigation Analysis

6. Conclusion

Key Takeaways from on-die Mitigation Analysis

Takeaway 1

A modern HBM2 chip **implements** an **undisclosed** on-DRAM-die RowHammer mitigation

Takeaway 2

This mitigation **resembles the one in DDR4 chips** from one major manufacturer as shown in prior work

On-Die RowHammer Mitigation Analysis (I)

HBM2 standard defines a “Target Row Refresh (TRR)-mode”

- Memory controller and DRAM **cooperate** to prevent RH bitflips

Real DDR4 chips implement **on-die mitigation** mechanisms

- Memory-controller-**transparent**, **hidden** behind periodic REF

*Does a similar **hidden** mitigation mechanism exist in HBM2?*

On-Die RowHammer Mitigation Analysis (II)

Hassan et al., "[Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications](#)," in MICRO, 2021.

Uncovering In-DRAM RowHammer Protection Mechanisms: A New Methodology, Custom RowHammer Patterns, and Implications

Hasan Hassan[†]

[†]ETH Zürich

Yahya Can Tuğrul^{†‡}

Kaveh Razavi[†]

[‡]TOBB University of Economics & Technology

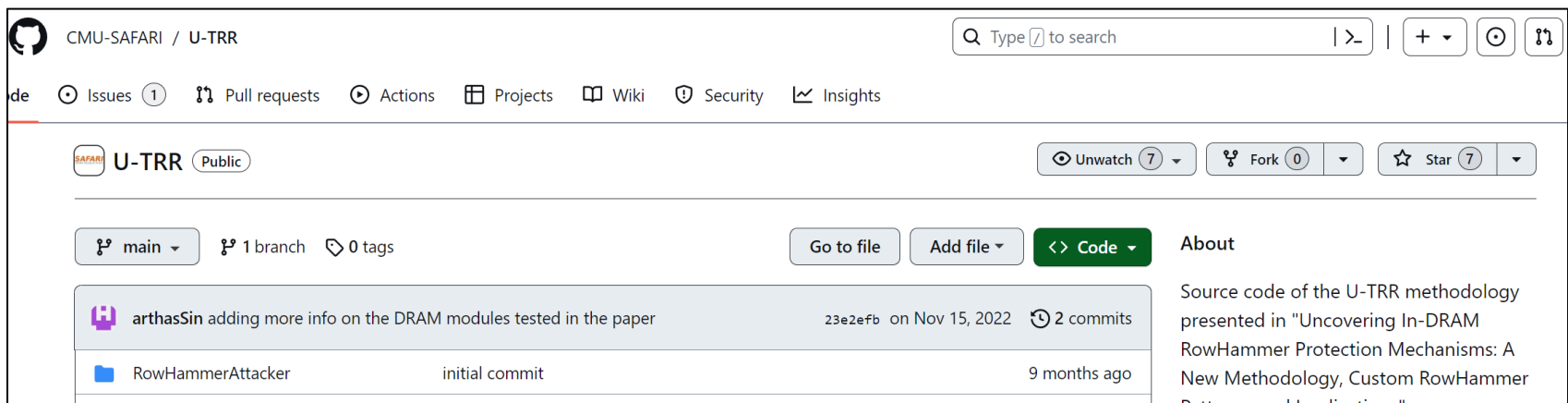
Jeremie S. Kim[†]

Onur Mutlu[†]

^σQualcomm Technologies Inc.

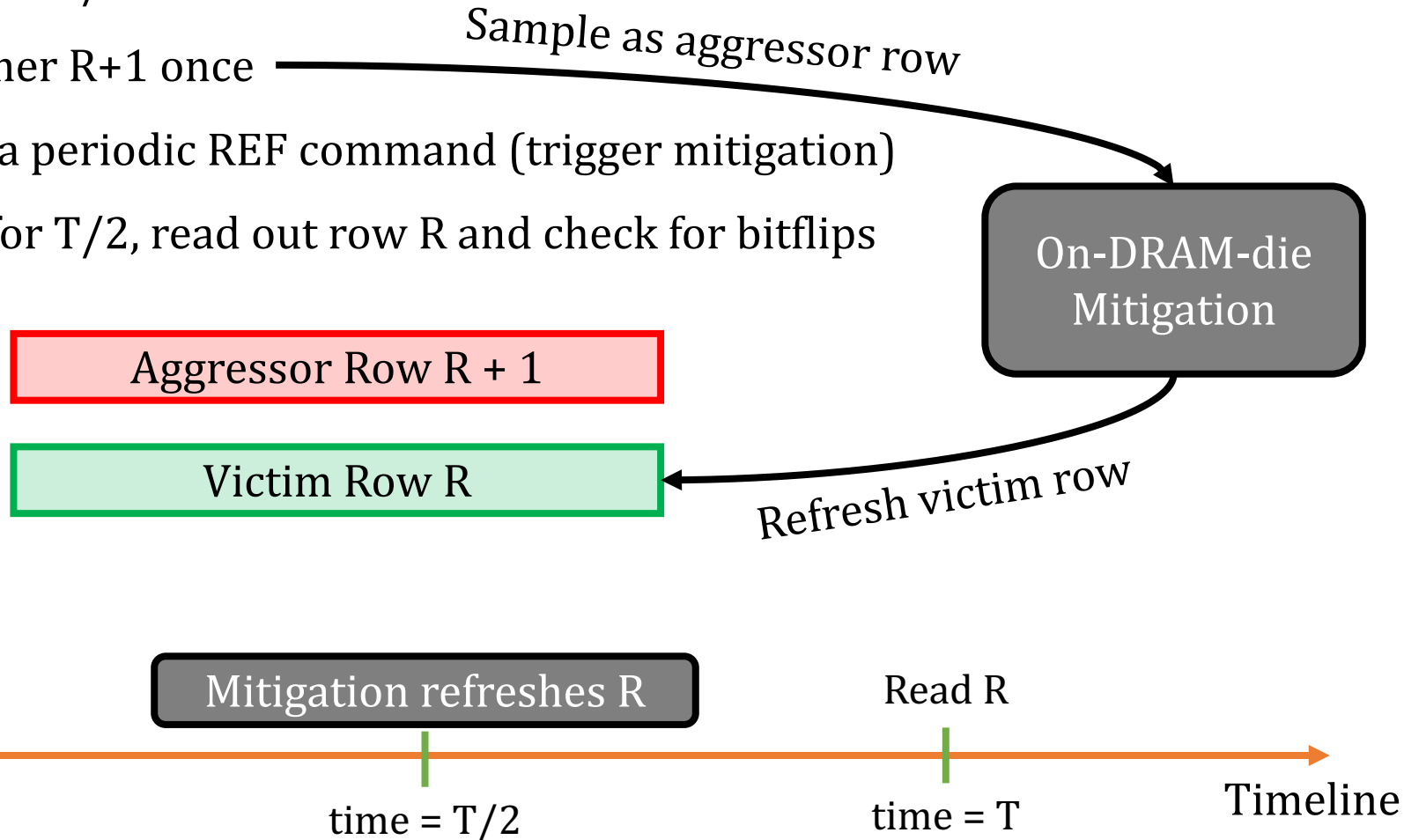
Victor van der Veen^σ

Key idea: Use **data retention failures** as a side channel to **detect when a row is refreshed** by on-die mitigation



Experimental Methodology

1. Identify a row (R) with T retention time
2. Wait for $T/2$
3. Hammer $R+1$ once
4. Issue a periodic REF command (trigger mitigation)
5. Wait for $T/2$, read out row R and check for bitflips



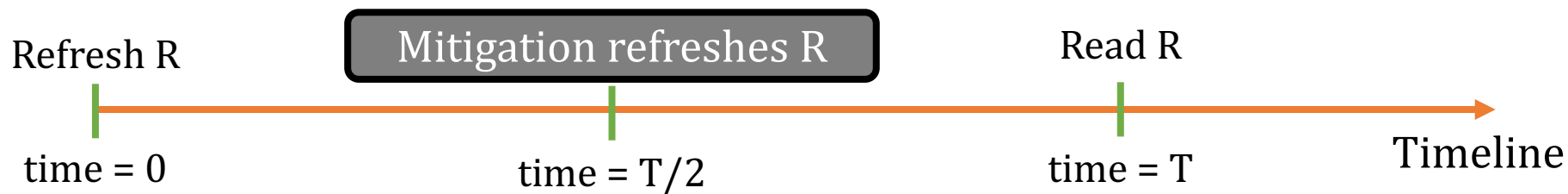
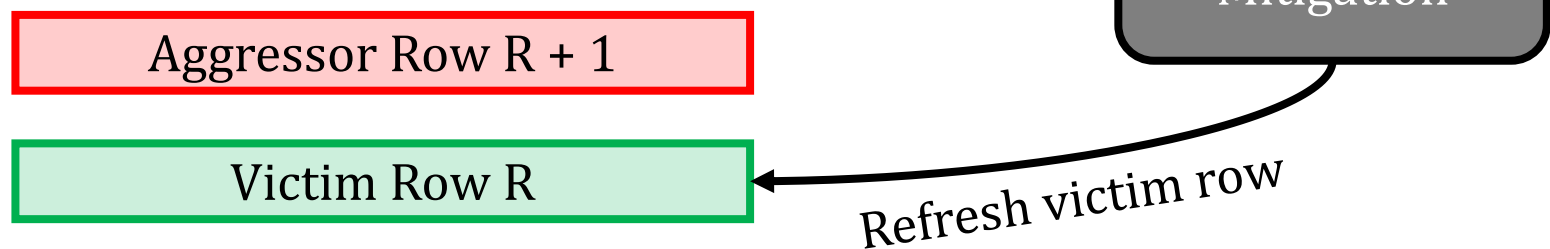
Experimental Methodology

1. Identify a row (R) with T retention time

Row R experiences no bitflips
only if on-DRAM-die mitigation exists

4. Issue a periodic REF command (trigger mitigation)

5. Wait for $T/2$, read out row R and check for bitflips



Experimental Methodology

1. Identify a row (R) with T retention time

Row R experiences no bitflips
only if on-DRAM-die mitigation exists

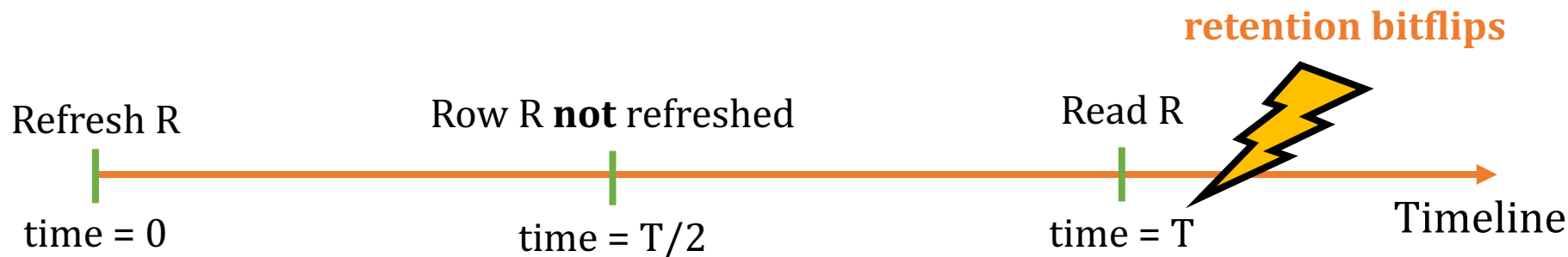
4. Issue a periodic REF command (trigger mitigation)

5. Wait for $T/2$, read out row R and check for bitflips

Row R experiences retention bitflips
if not refreshed at $T/2$

Victim Row R

Refresh victim row



HBM2 DRAM Chips Implement Undisclosed TRR

The HBM2 chip **implements** an **undisclosed** on-die RowHammer mitigation mechanism

This mechanism **performs** a victim row refresh operation every **17** periodic refresh (REF) operations

This mitigation **resembles the one in DDR4 chips** from one major manufacturer

Outline

1. HBM DRAM Organization & Operation
2. DRAM Cell Leakage & RowHammer
3. HBM DRAM Testing Methodology
4. RowHammer Spatial Variation Analysis
5. On-die RowHammer Mitigation Analysis
6. Conclusion

Conclusion

We provide the **first detailed experimental characterization** of **RowHammer** in a modern **HBM2** DRAM chip

Different **channels** in 3D-stacked HBM chips exhibit **different RowHammer vulnerability**

DRAM **rows near the end of a DRAM bank** are more RowHammer **resilient**

Two implications for RowHammer **attacks and mitigations**:

1. Faster and more effective attacks
2. More efficient mitigations

A modern HBM chip **implements** undisclosed on-DRAM-die RowHammer mitigation (e.g., similar to DDR4 chips)

Future Directions: To present more insights into how RowHammer behaves in HBM

1. Test **more** HBM DRAM chips, data patterns, at different temperature and voltage levels
2. Investigate read-disturb-based interference **across different 3D-stacked HBM DRAM channels**
3. Study the effects of the **new** read-disturb phenomenon, **RowPress [Luo+, ISCA'23]**

<https://arxiv.org/abs/2305.17918>

arXiv > cs > arXiv:2305.17918

Search...

All fields

Search

Help | Advanced Search

Computer Science > Cryptography and Security

[Submitted on 29 May 2023]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun, Majd Osseiran, Abdullah Giray Yağlıkçı, Yahya Can Tuğrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez Luna, Onur Mutlu

RowHammer (RH) is a significant and worsening security, safety, and reliability issue of modern DRAM chips that can be exploited to break memory isolation. Therefore, it is important to understand real DRAM chips' RH characteristics. Unfortunately, no prior work extensively studies the RH vulnerability of modern 3D-stacked high-bandwidth memory (HBM) chips, which are commonly used in modern GPUs.

In this work, we experimentally characterize the RH vulnerability of a real HBM2 DRAM chip. We show that 1) different 3D-stacked channels of HBM2 memory exhibit significantly different levels of RH vulnerability (up to 79% difference in bit error rate), 2) the DRAM rows at the end of a DRAM bank (rows with the highest addresses) exhibit significantly fewer RH bitflips than other rows, and 3) a modern HBM2 DRAM chip implements undisclosed RH defenses that are triggered by periodic refresh operations. We describe the implications of our observations on future RH attacks and defenses and discuss future work for understanding RH in 3D-stacked memories.

Comments: To appear at DSN Disrupt 2023

Subjects: **Cryptography and Security (cs.CR)**; Hardware Architecture (cs.AR)

Cite as: [arXiv:2305.17918](https://arxiv.org/abs/2305.17918) [cs.CR]

(or [arXiv:2305.17918v1](https://arxiv.org/abs/2305.17918v1) [cs.CR] for this version)

<https://doi.org/10.48550/arXiv.2305.17918> 

Download:

- [PDF](#)
- [Other formats](#)



Current browse context:

cs.CR

[< prev](#) | [next >](#)
[new](#) | [recent](#) | [2305](#)

Change to browse by:

[cs](#)
[cs.AR](#)

References & Citations

- [NASA ADS](#)
- [Google Scholar](#)
- [Semantic Scholar](#)

Export BibTeX Citation

Bookmark



An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Link/QR code to full paper

<https://arxiv.org/pdf/2305.17918>



Ataberk Olgun Majd Osseiran

A. Giray Yağlıkçı Yahya Can Tuğrul Haocong Luo Steve Rhyner

Behzad Salami Juan Gomez Luna Onur Mutlu

ETH zürich

SAFARI



AMERICAN
UNIVERSITY
OF BEIRUT

Understanding Read Disturbance in High Bandwidth Memory: An Experimental Analysis of Real HBM2 DRAM Chips

- Tests 5 more HBM2 chips
- Tests more DRAM components (e.g., banks and rows) per chip
- Analyzes hammer counts to induce more than one bitflip ($HC_{\text{second, third, ... , tenth}}$)
- Analyzes the RowPress vulnerability of HBM2 chips
- Further reverse engineers the on-DRAM-die RH defense mechanism

Methodology

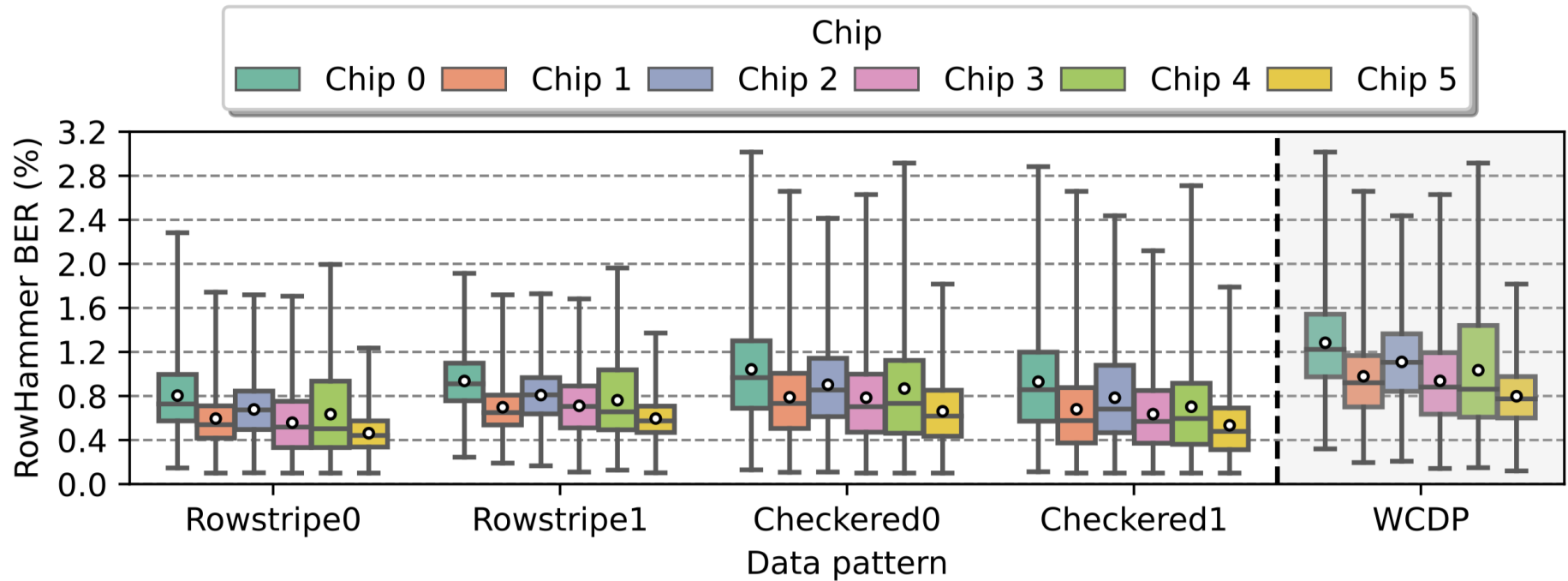
TABLE II
TESTED DRAM COMPONENTS FOR EACH EXPERIMENT TYPE

| Experiment Type | Rows (Per Bank) | Banks | Pseudo Channels | Channels |
|------------------------|-----------------|-------|-----------------|----------|
| RowHammer BER | 16384 | 1 | 1 | 8 |
| RowHammer HC_{first} | 3072 | 3 | 2 | 8 |
| RowPress BER | 384 | 1 | 1 | 3 |
| RowPress HC_{first} | 384 | 1 | 1 | 3 |

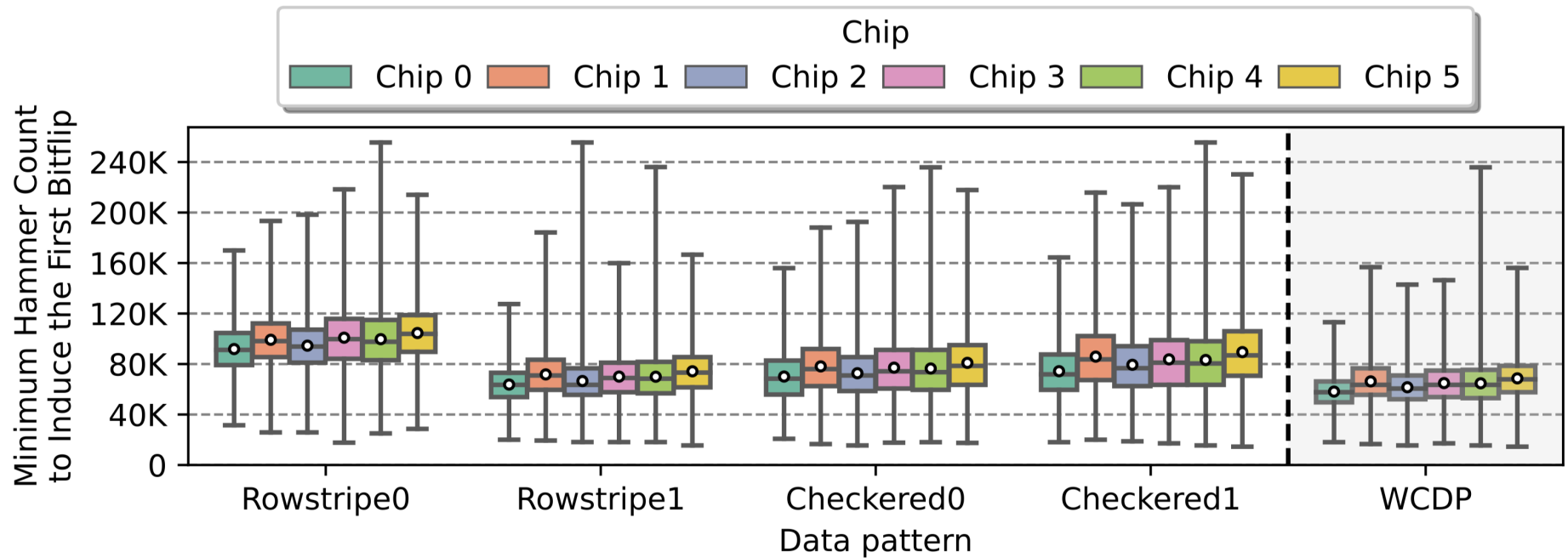
TABLE III
LABELS FOR THE HBM2 CHIPS IN EACH TESTED FPGA BOARD

| FPGA Board | Chip Label |
|----------------------|--------------------|
| Bittware XUPV VH | Chip 0 |
| AMD Xilinx Alveo U50 | Chip 1, 2, 3, 4, 5 |

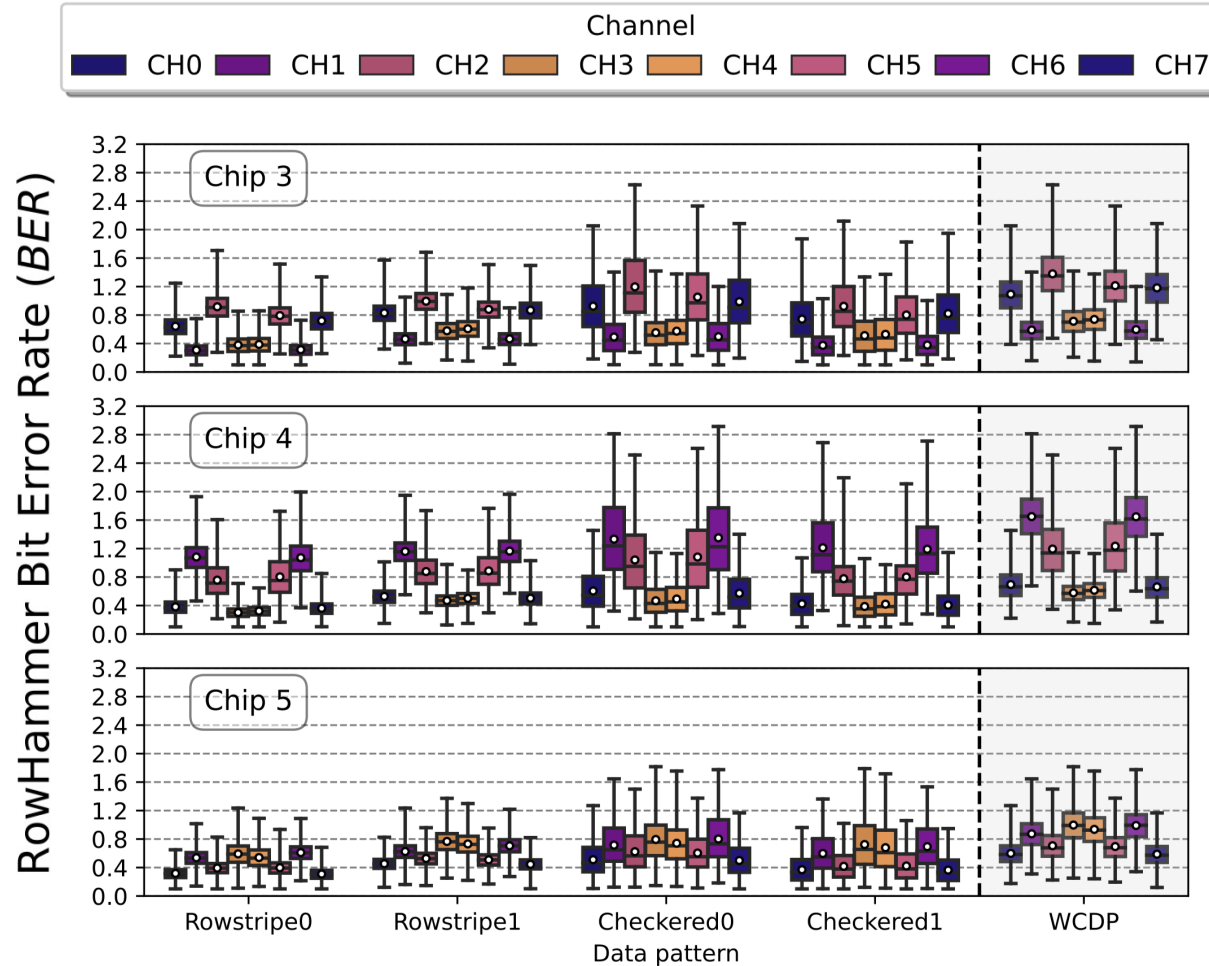
RowHammer BER Across Chips



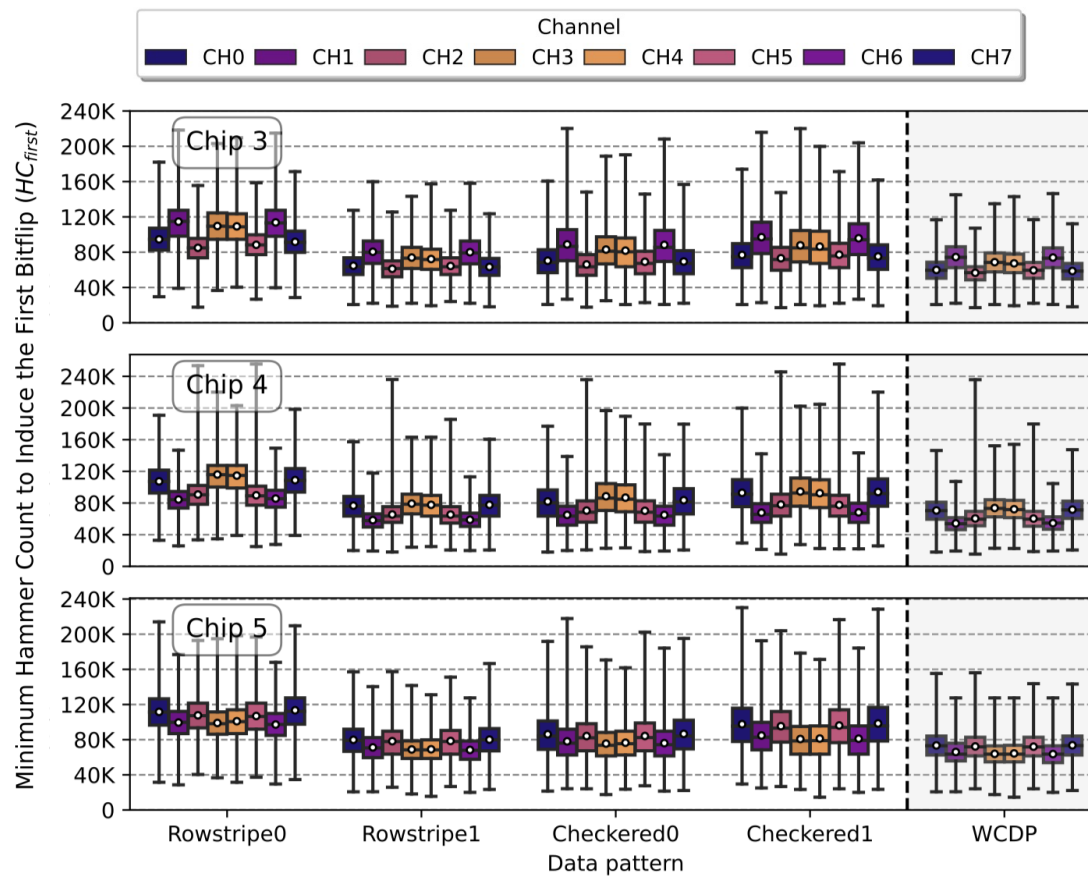
RowHammer HC_{first} Across Chips



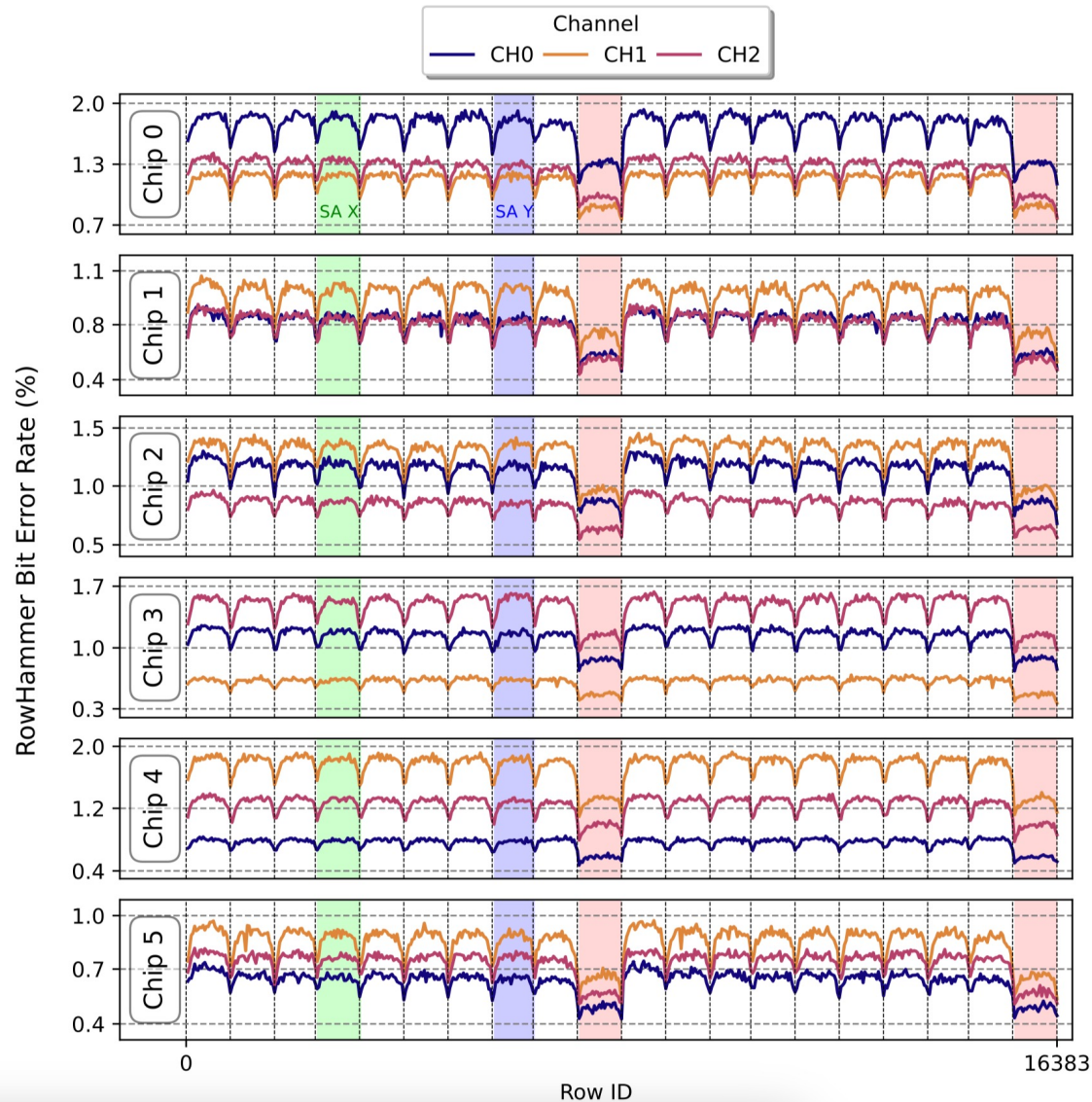
RowHammer BER Across Channels



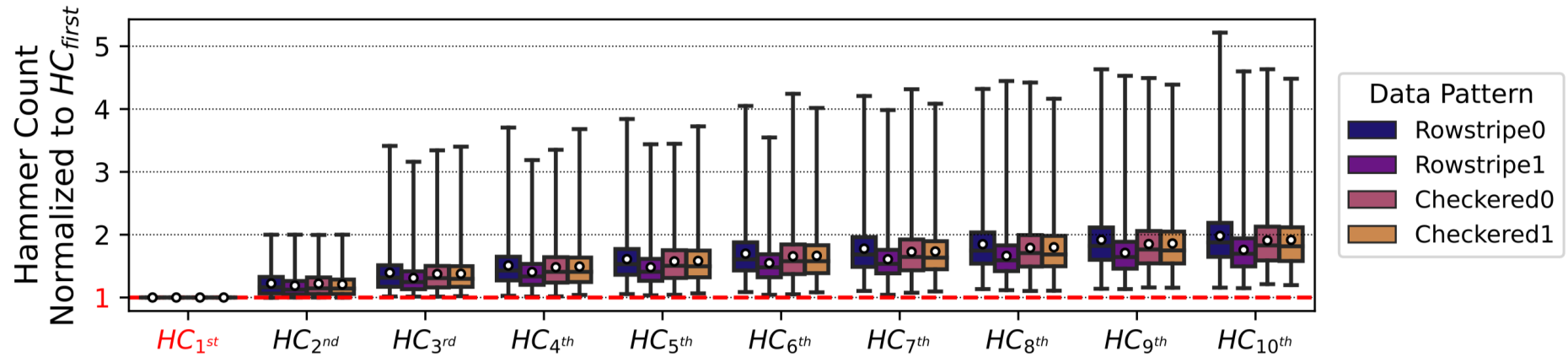
RowHammer HC_{first} Across Channels



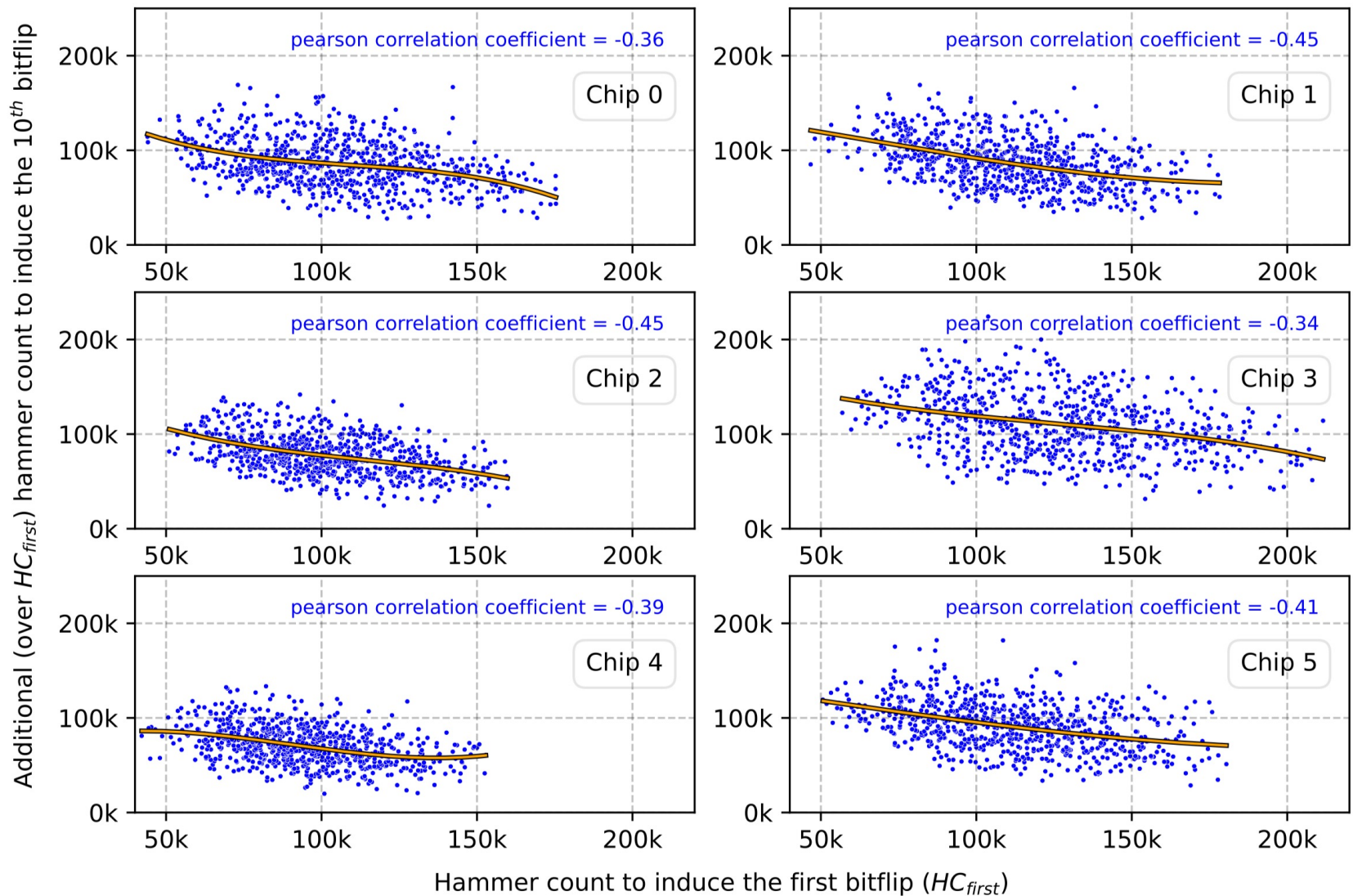
RowHammer BER Across Rows



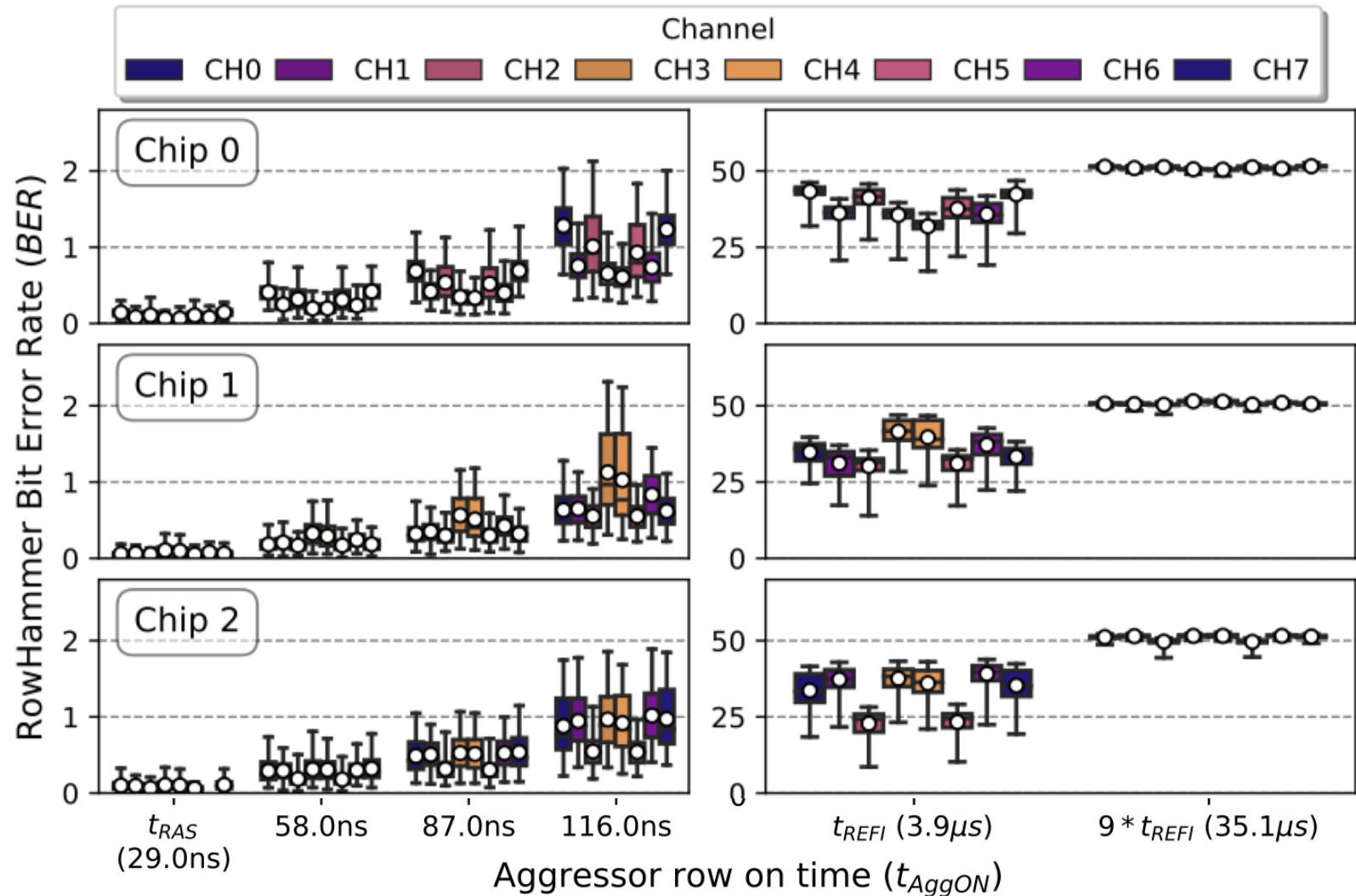
RowHammer's Sensitivity to Hammer Count (I)



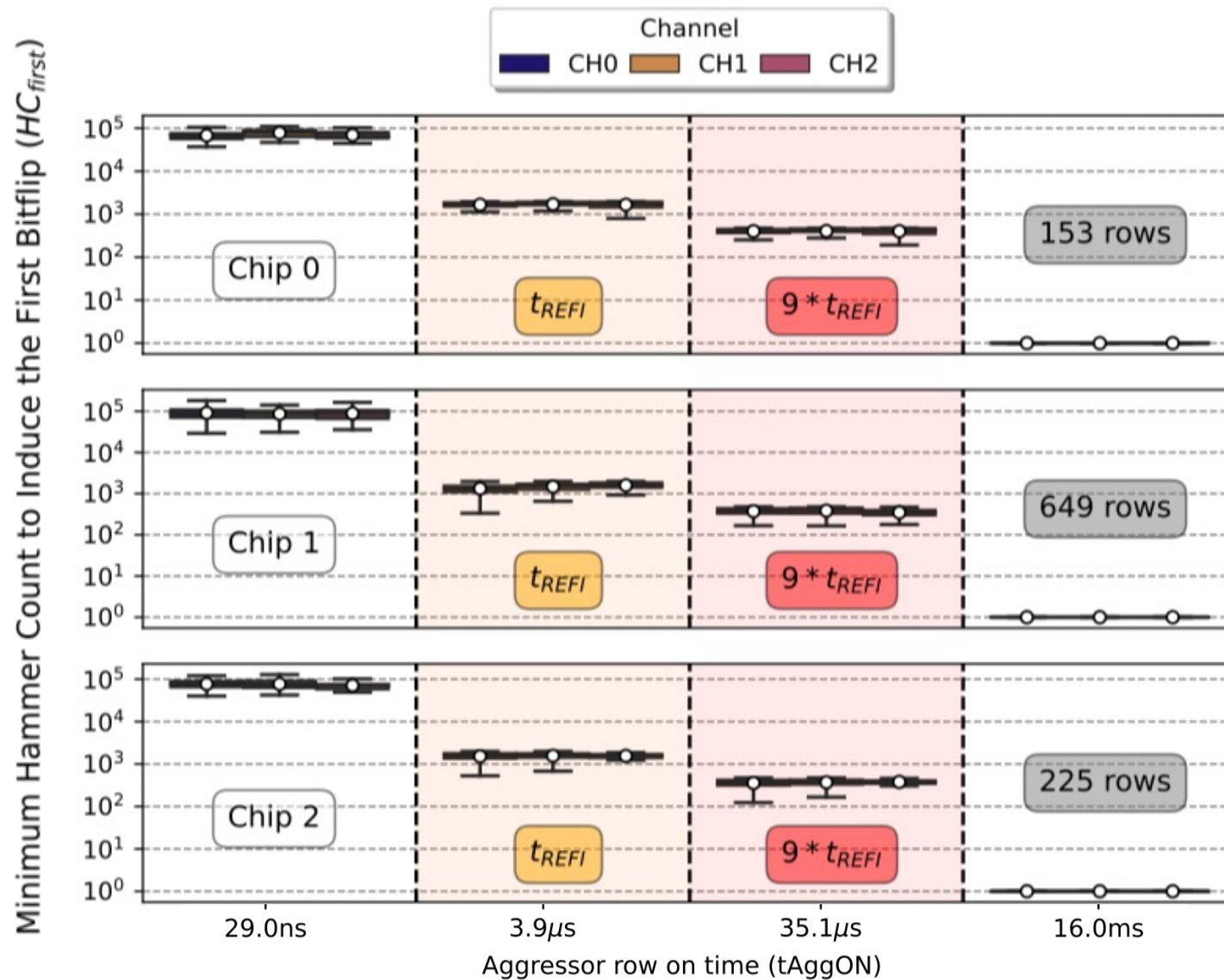
RowHammer's Sensitivity to Hammer Count (II)



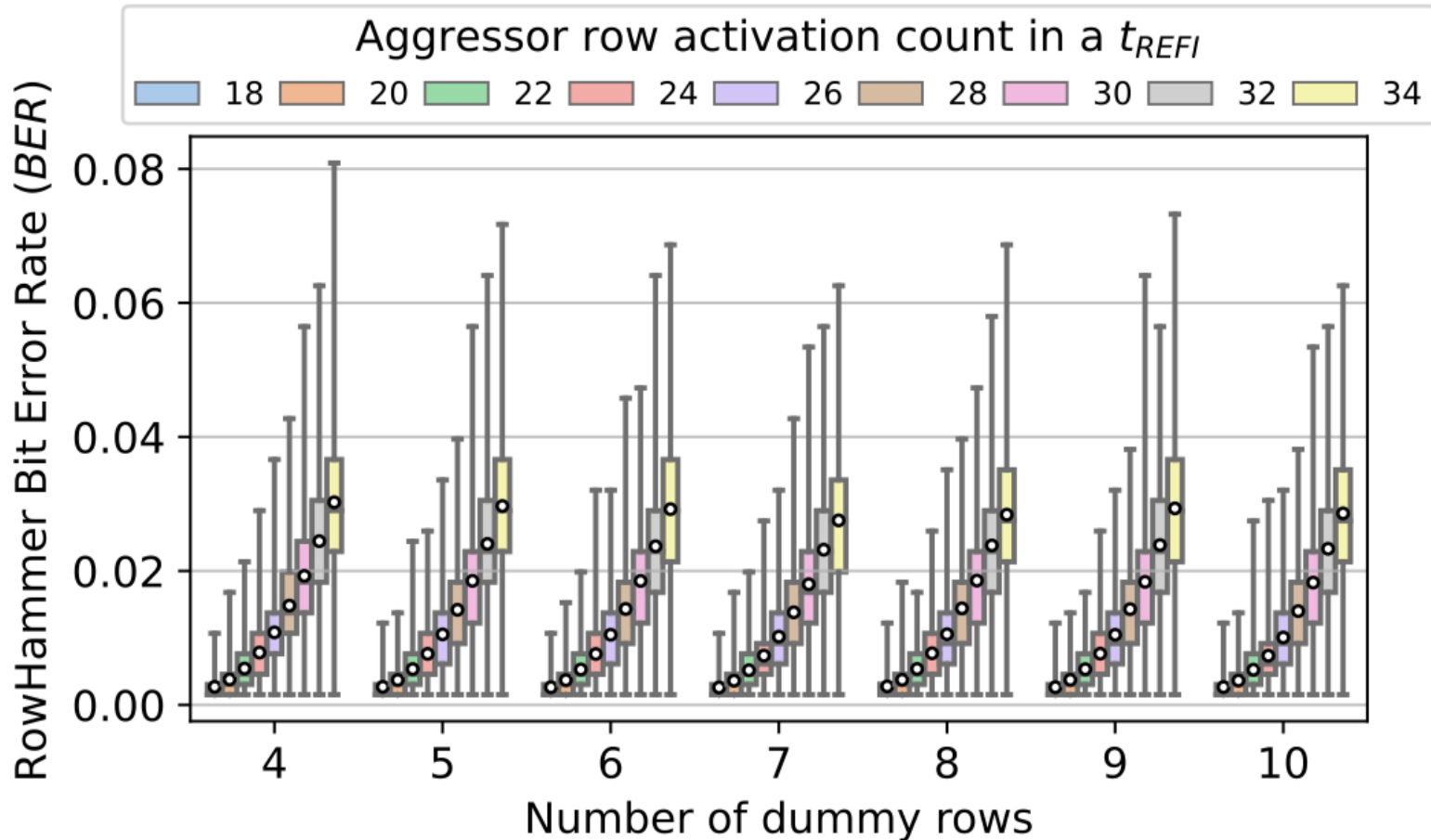
RowPress BER Across Channels



RowPress HC_{first} Across Channels



Attack Patterns to Bypass Undisclosed TRR



Silicon Level RowHammer and RowPress Mechanisms

Major RowHammer Silicon Mechanisms (I)

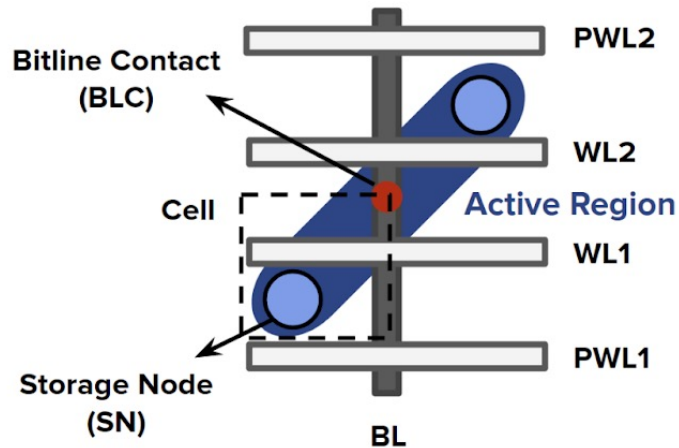
- There are two major silicon-level causes for RowHammer bitflips [1, 7].
- First, **capacitive coupling between the physically-adjacent aggressor and victim wordlines causes crosstalk.**
 - When the aggressor wordline is activated, the potential of the victim wordlines also increases [10], causing an increase in the access transistor subthreshold leakage of the victim cell [1, 4].
 - When the aggressor wordline is repeatedly activated many times, the accumulation of the increased subthreshold leakage causes bitflips.
- Second, **repeated switching of the channel of the access transistor of the aggressor cell injects electrons into the storage node of the victim cell, causing it to lose charge** [1 - 5].
 - The injected electrons mainly come from two sources.
 - First, when the aggressor access transistor is switched off, the diffused channel electrons are attracted to the storage node of the victim cell [2, 3, 6, 8]. This is because the victim cell's storage node has a higher potential compared to the bitline [2]. These electrons recombine with the stored charge in the victim cell, reducing the cell potential, and eventually causing a bitflip.
 - Second, the interface charge traps of the aggressor access transistor traps electrons during the activation of the victim row [4, 5, 8]. Later, when the aggressor row is closed, the trapped electrons are released and find their way to the storage node of the victim cell.

Major RowHammer Silicon Mechanisms (II)

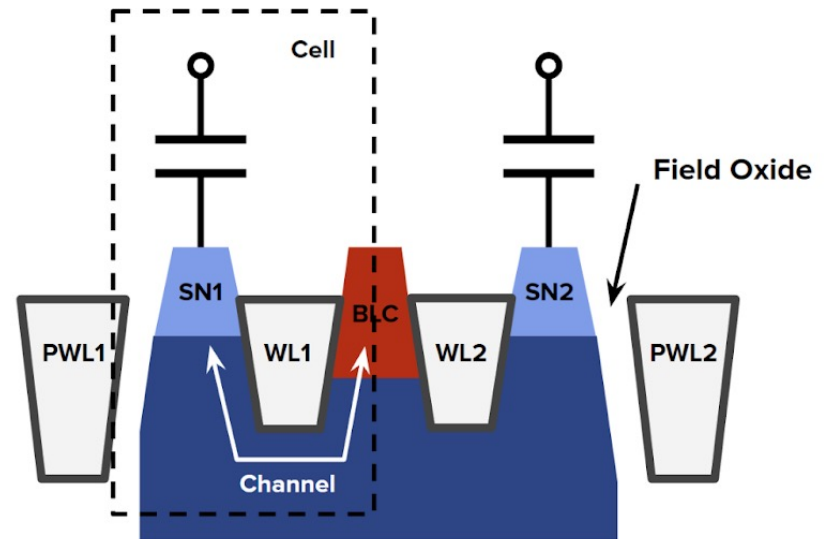
- Although existing literature [1-6] suggests that both capacitive crosstalk between wordlines and electron migration and injection are the two fundamental silicon-level mechanisms for RowHammer bitflips, they do not quantitatively compare the contribution of these two mechanisms to make out a dominant cause for RowHammer.
- A recent work [9] investigates how each mechanism contributes to the significantly increased RowHammer vulnerability (i.e., requiring much less aggressor row activation to induce a bitflip) of the double-sided access pattern.
- The key takeaway of [9] is that the **trap-assisted electron migration & injection is the dominant mechanism for the increased vulnerability to double-sided RowHammer** (i.e., requiring fewer aggressor row activations to induce a bitflip) compared to single-sided, while **capacitive crosstalk is not a major factor in the increased vulnerability to double-sided RowHammer** compared to single-sided.

Silicon-Level RH: Pictorial Illustration (I)

- Figure 1 illustrates the physical layout of DRAM.
- Figure 2 shows how electrons are injected into the victim cell.



a) Top View



b) Cross Section

Figure 1. DRAM Physical Layout (Figurative)

Silicon-Level RH: Pictorial Illustration (II)

- Figure 2a) shows the initial state, where WL1 is the aggressor wordline and SN2 is the storage node of the victim cell, which is initially positively charged.
- When the aggressor wordline is open (Figure 2b), excessive electrons are concentrated in the aggressor's channel ① due to channel inversion and/or interface traps.
- When the aggressor wordline is closed, the channel inversion layer collapses (and/or the trapped electrons get released), and some of the excessive electrons can migrate and inject into the victim cell ②.

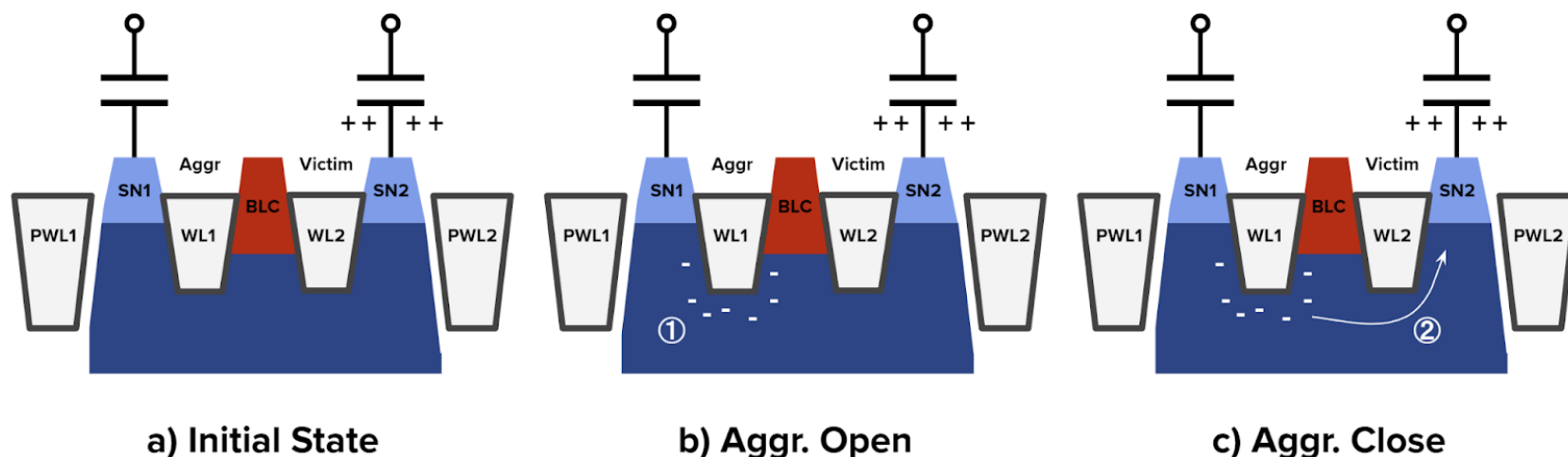


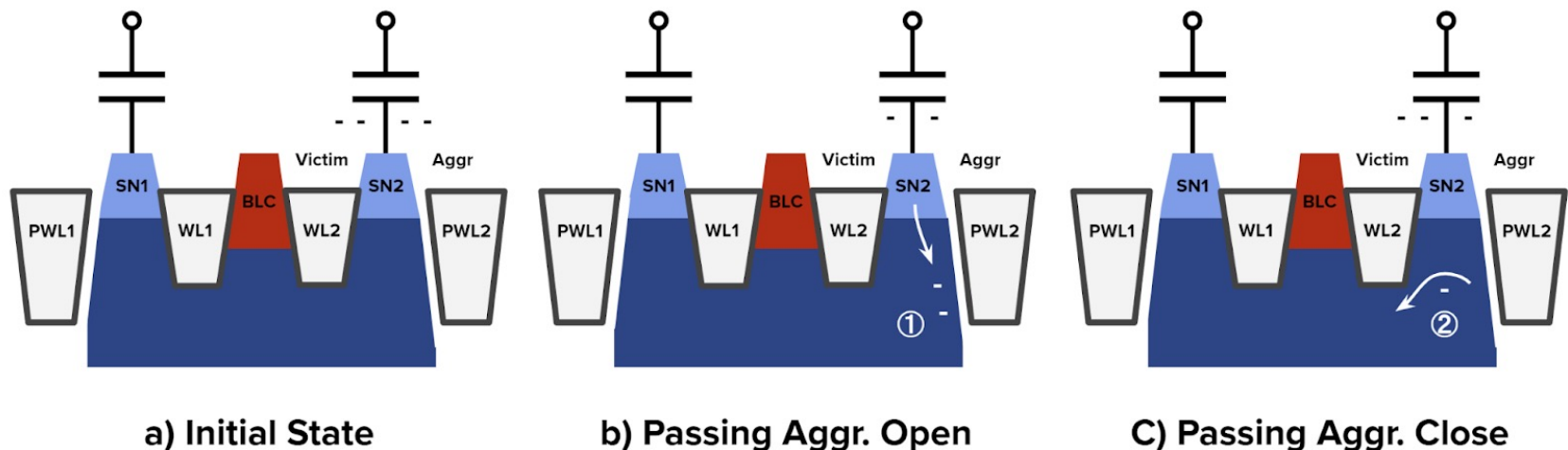
Figure 2. Electron Migration & Injection (Figurative)

RH Silicon Mechanism References

- [1] Walker et al., "On DRAM Rowhammer and the Physics of Insecurity," in IEEE Transactions on Electron Devices, 2021
- [2] Park et al., "Experiments and root cause analysis for active-precharge hammering fault in DDR3 SDRAM under $3 \times \text{nm}$ technology," in Microelectronics Reliability, 2016
- [3] Yang et al., "Suppression of Row Hammer Effect by Doping Profile Modification in Saddle-Fin Array Devices for Sub-30-nm DRAM Technology," in IEEE Transactions on Device and Materials Reliability, 2016
- [4] Ryu et al., "Overcoming the Reliability Limitation in the Ultimately scaled DRAM using Silicon Migration Technique by Hydrogen Annealing," in Technical Digest - International Electron Devices Meeting, IEDM, 2018
- [5] Yang et al., "Trap-Assisted DRAM Row Hammer effect," in IEEE Electron Device Letters, 2019
- [6] Gautam et al., "Row Hammering Mitigation Using Metal Nanowire in Saddle Fin DRAM," in IEEE Transactions on Electron Devices, 2019
- [7] Han et al., "Surround Gate Transistor With Epitaxially Grown Si Pillar and Simulation Study on Soft Error and Rowhammer Tolerance for DRAM," in IEEE Transactions on Electron Devices, 2021
- [8] Park et al., "Row Hammer Reduction Using a Buried Insulator in a Buried Channel Array Transistor," in IEEE Transactions on Electron Devices, 2021
- [9] Zhou et al., "Double-sided Row Hammer Effect in Sub-20 nm DRAM: Physical Mechanism, Key Features and Mitigation," in IEEE International Reliability Physics Symposium (IRPS), 2023
- [10] Redeker et al., "An Investigation into Crosstalk Noise in DRAM Structures," in Proceedings of the 2002 IEEE International Workshop on Memory Technology, Design and Testing (MTDT), 2002

Major RowPress Silicon Mechanism

- RowPress causes bitflips by keeping the aggressor row open for a long period of time. One silicon-level mechanism to explain RowPress is called **the passing gate effect** [11, 12].
- Figure 3 shows how the passing gate effect causes bitflips.
- In the initial state (Figure 3.a), SN2 is the victim and the passing wordline PWL2 is the aggressor. The victim cell is initially negatively charged.
- When PWL2 is kept open (Figure 3.b), it keeps attracting electrons from the victim cell ①.
- When PWL2 is closed (Figure 3.c), not all the attracted electrons will return to the victim cell, causing leakage.



RP Silicon Mechanism References

[11] Hong et al., “DSAC: Low-Cost Rowhammer Mitigation Using In-DRAM Stochastic and Approximate Counting Algorithm,” arXiv:2302.03591 [cs.CR]

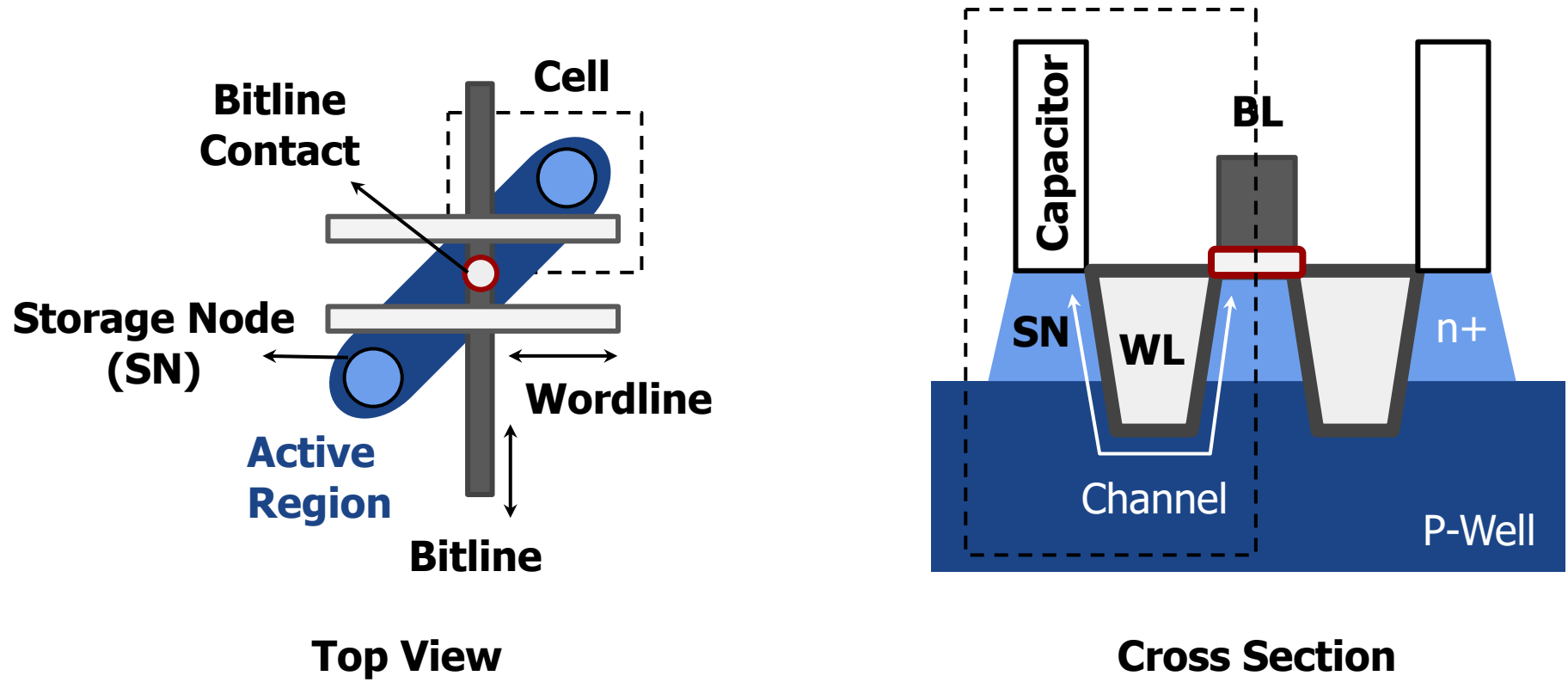
[12] Nam et al., “X-ray: Discovering DRAM Internal Structure and Error Characteristics by Issuing Memory Commands,” in IEEE CAL, 2023

Illustrations

Silicon-Level Disturbance Mechanism

Electron Migration & Injection

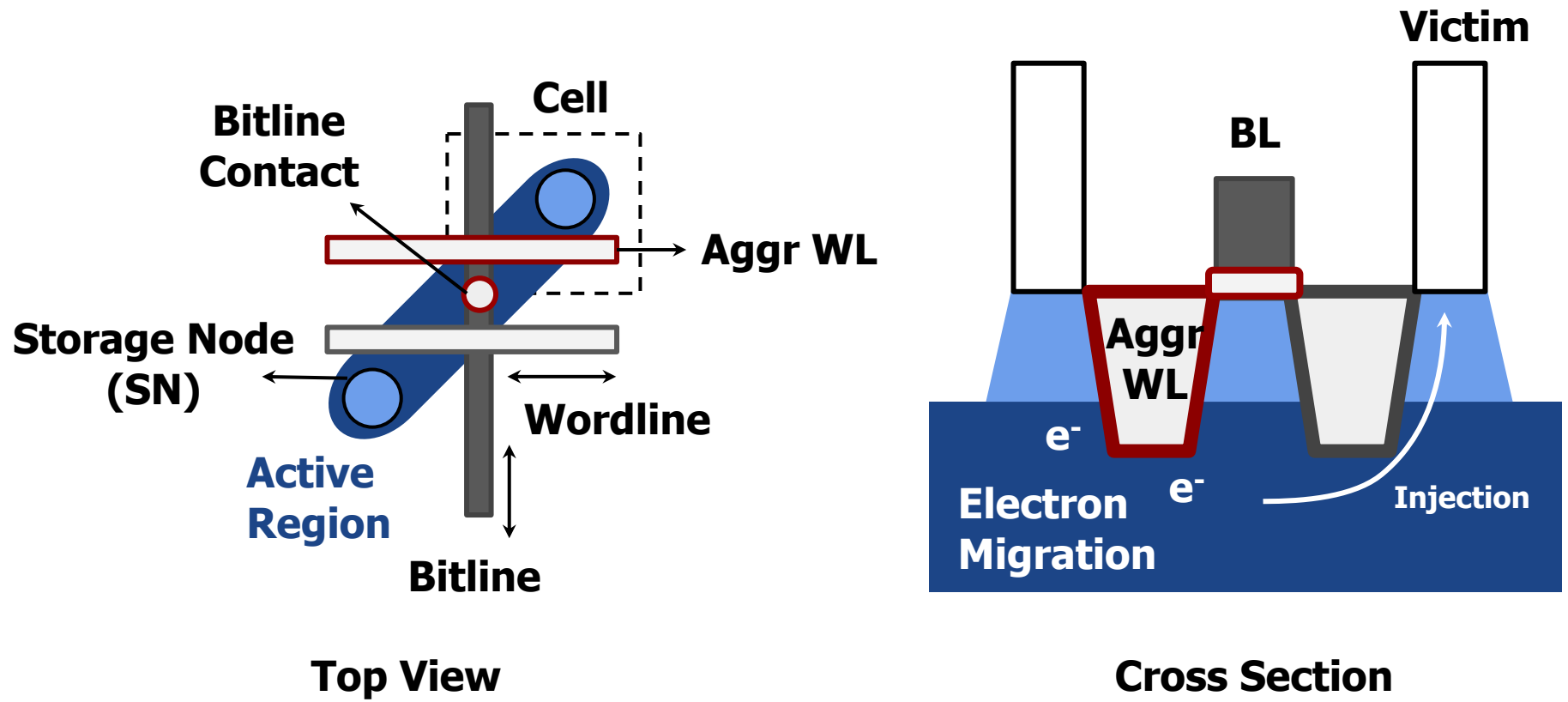
Figurative illustration of the physical layout of a DRAM cell



Silicon-Level Disturbance Mechanism

Electron Migration & Injection

High-level: Electrons migrate from the aggr channel to the victim node



Silicon-Level Disturbance Mechanism

Electron Migration & Injection

High-level: Electrons migrate from the aggr channel to the victim node

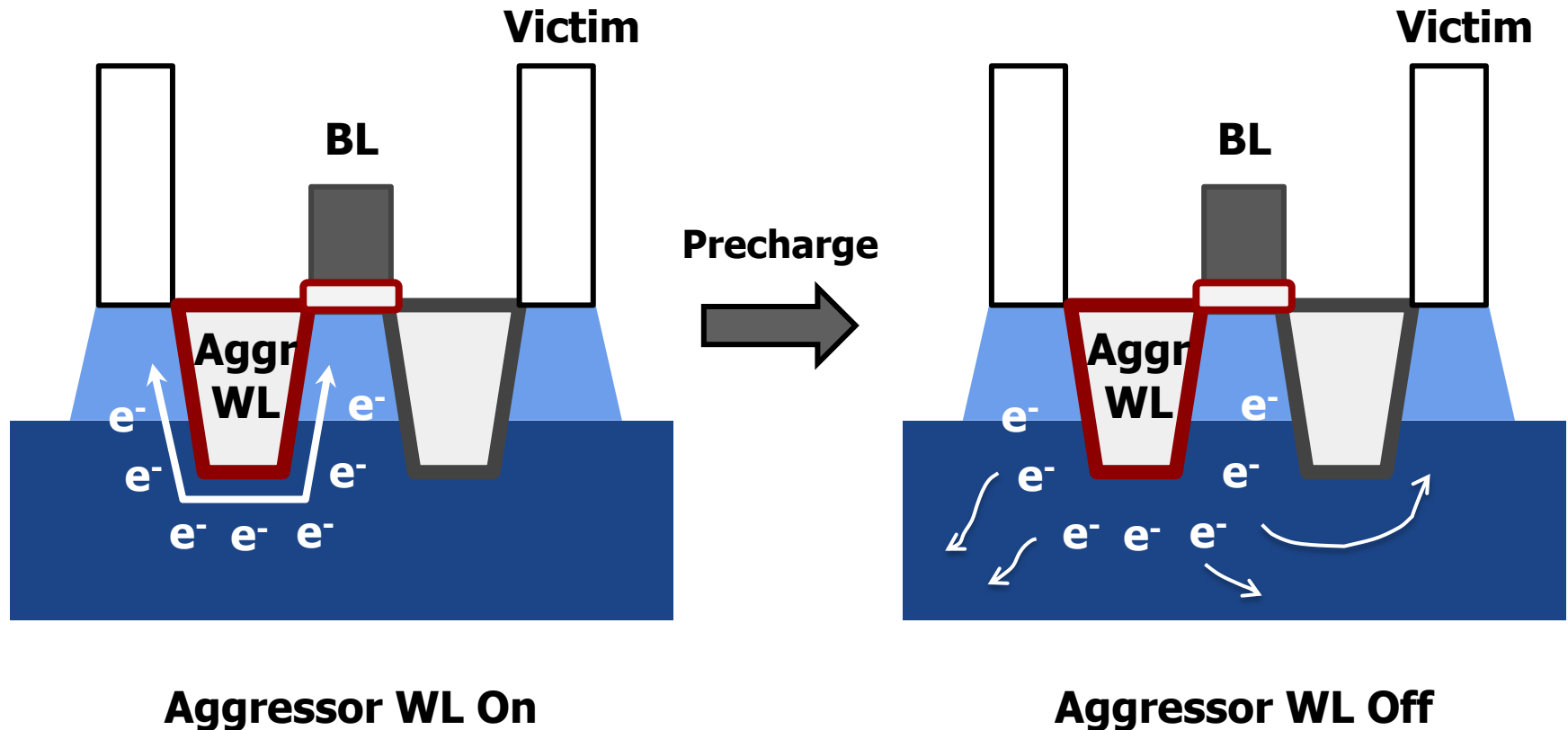
■ Sources of these electrons

- ❑ Collapse of the inversion layer of the aggressor row's access transistor channel when the aggressor WL is turned off
- ❑ Interface traps at the aggressor WL that capture electrons when the aggressor WL is open, and release them when the aggressor WL is off

Silicon-Level Disturbance Mechanism

Electron Migration & Injection

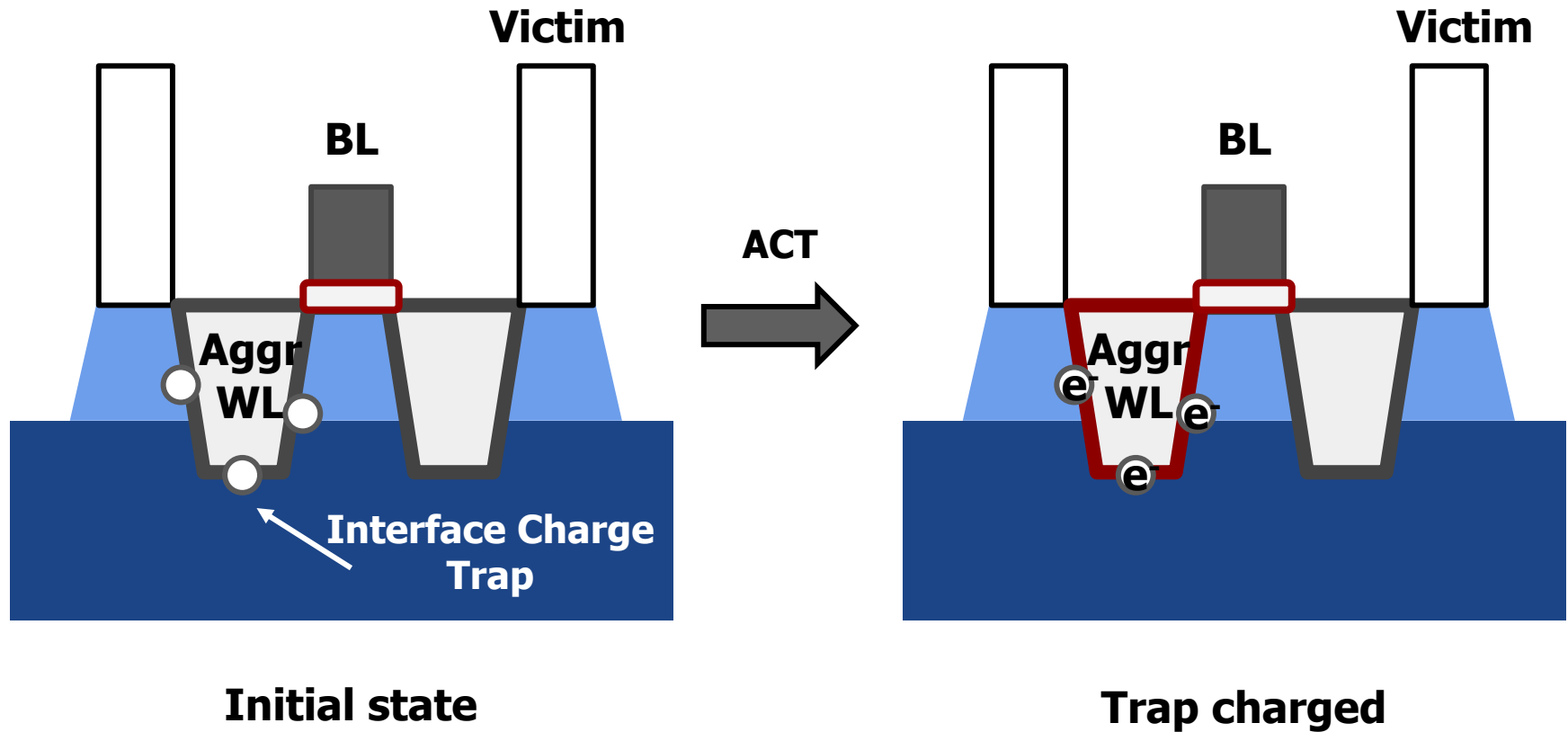
Inversion layer collapse in the aggr channel



Silicon-Level Disturbance Mechanism

Electron Migration & Injection

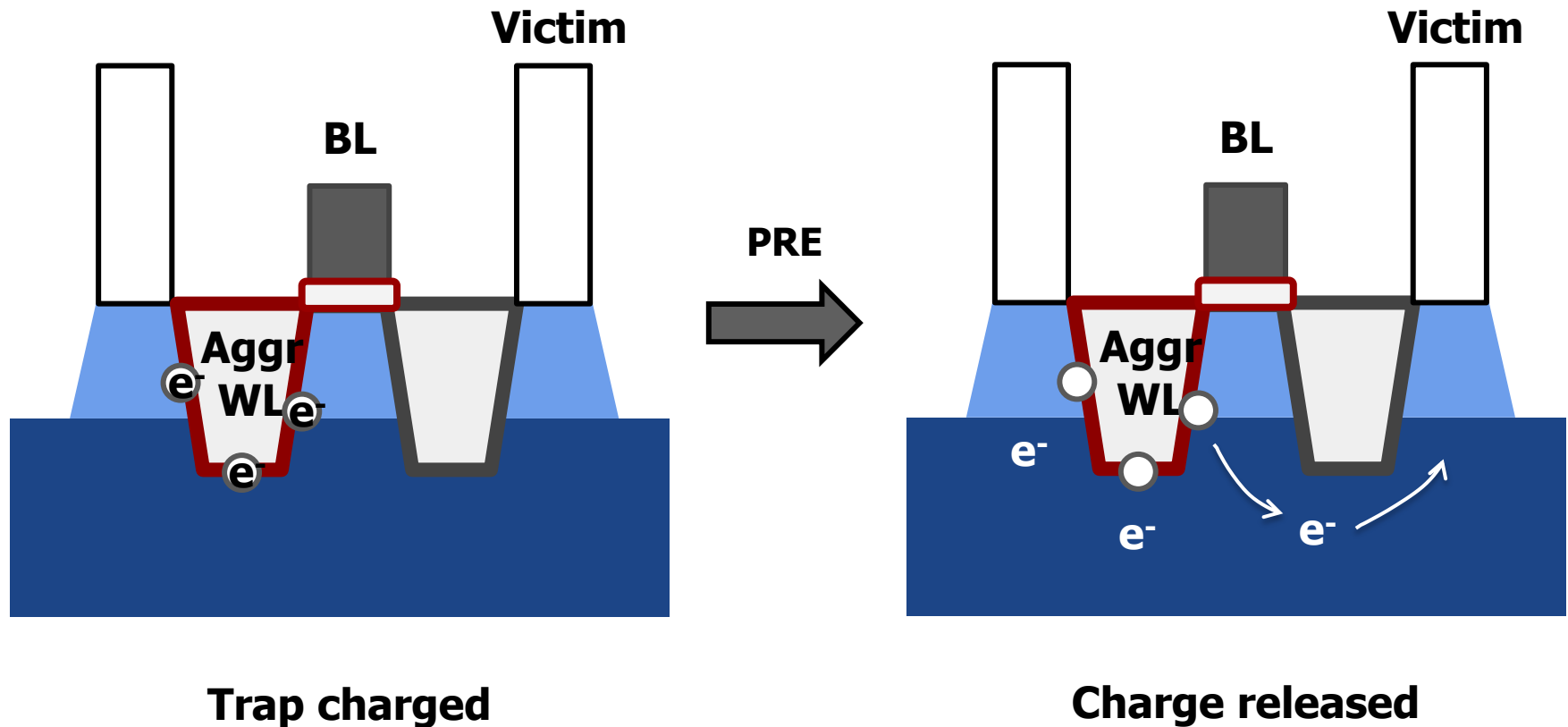
Interface charge trap



Silicon-Level Disturbance Mechanism

Electron Migration & Injection

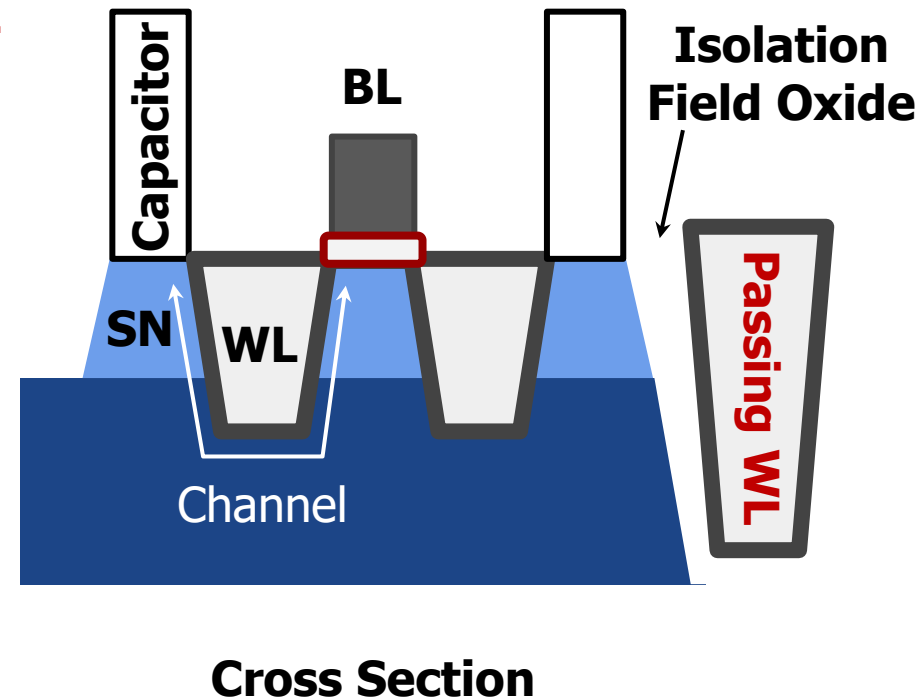
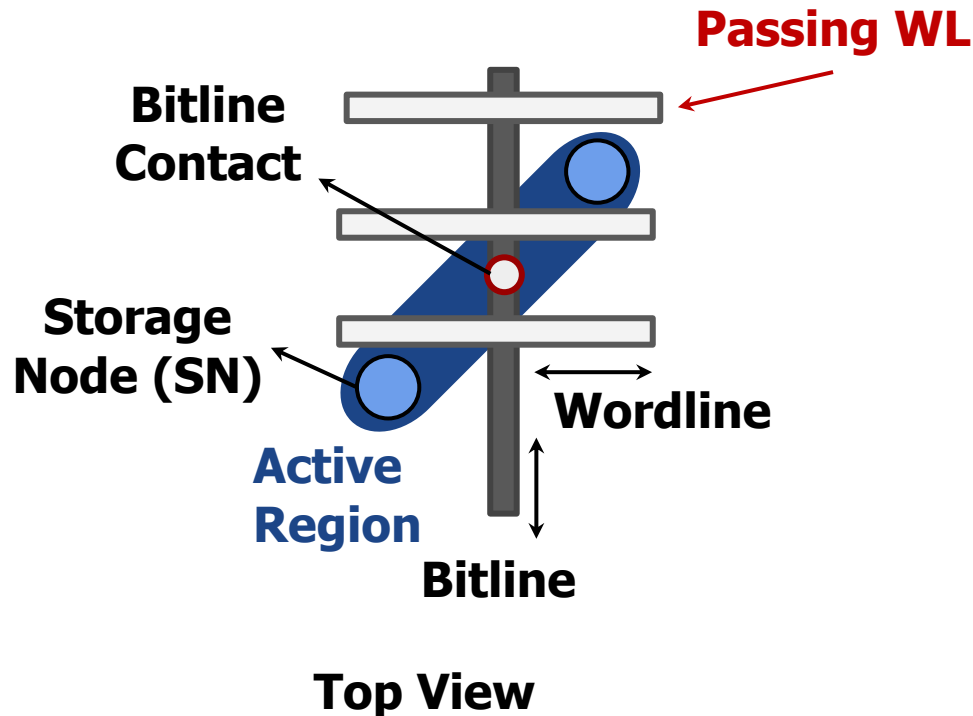
Interface charge trap



Silicon-Level Disturbance Mechanism

Passing Gate Effect

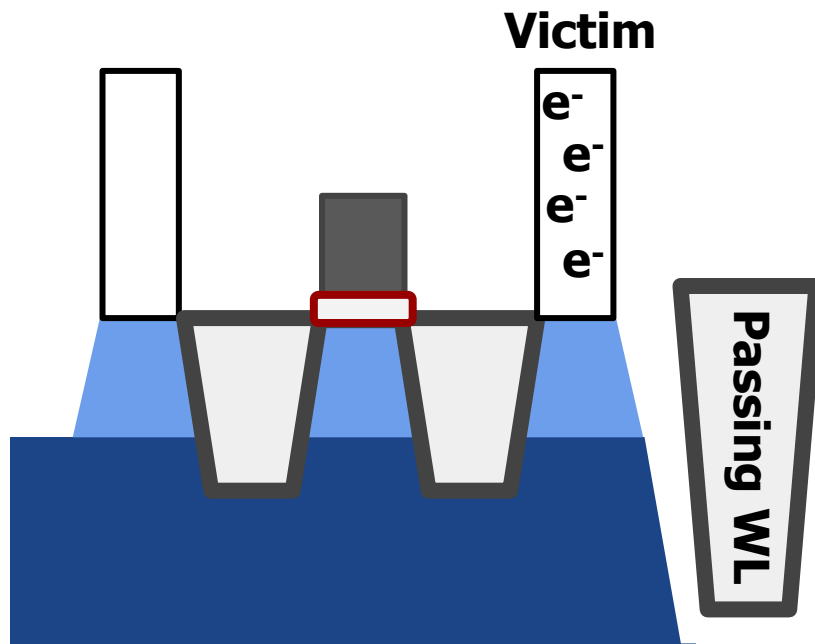
Figurative illustration of the physical layout of a DRAM cell



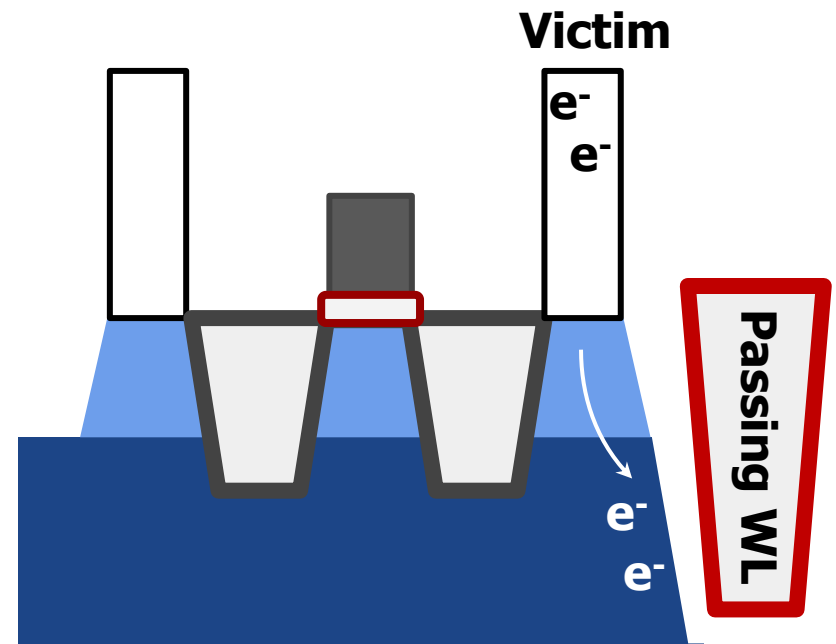
Silicon-Level Disturbance Mechanism

Passing Gate Effect

Attracts electrons from the victim



Initial state

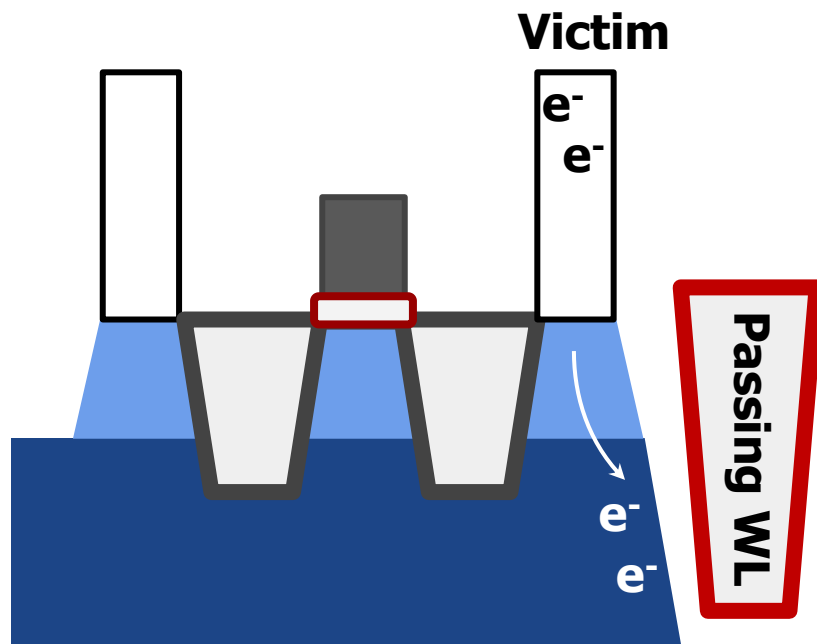


Passing WL On

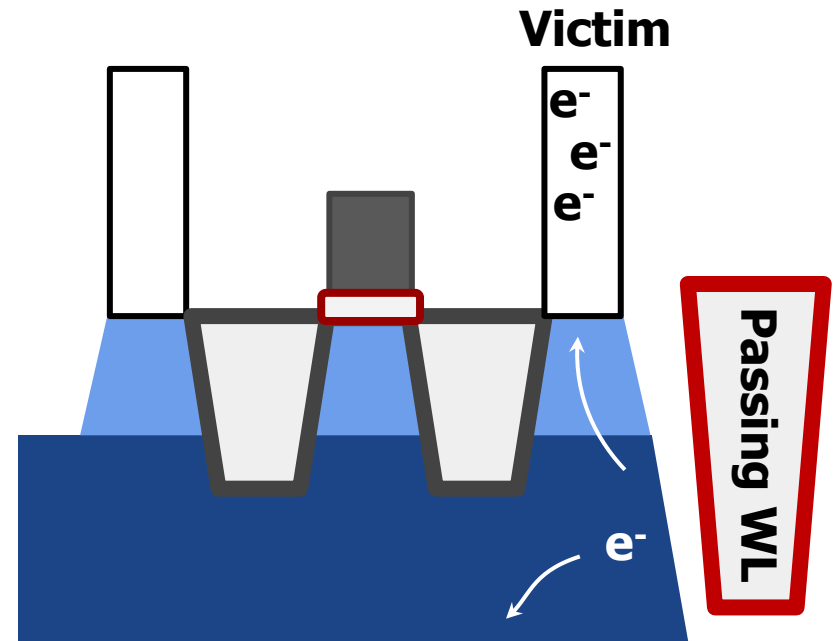
Silicon-Level Disturbance Mechanism

Passing Gate Effect

Attracts electrons from the victim



Passing WL On



Passing WL Off
(Some electrons do not return to the victim)

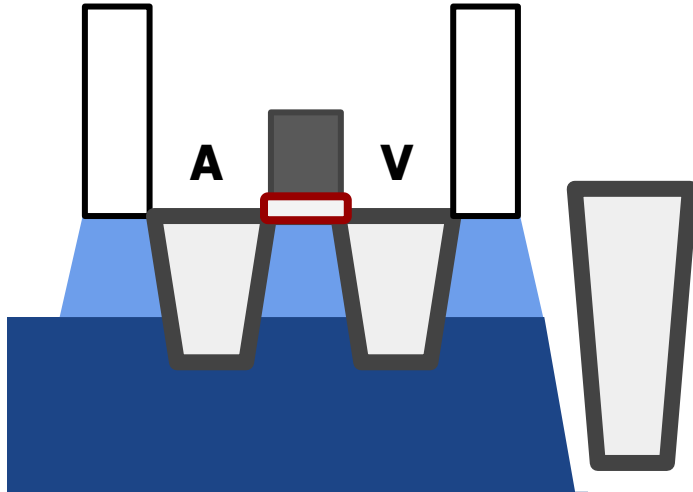
Silicon-Level Disturbance Mechanism

Passing Gate Effect

- The longer the passing WL is open, the more electrons it can attract from the victim.
- Major contributor to the RowPress vulnerability.

Access Pattern - RowHammer

Single-Sided - Case 1

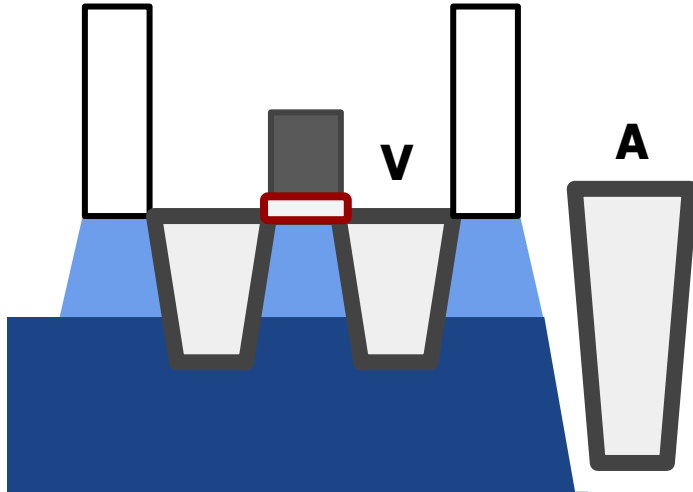


Contributing mechanisms

1. Increased subthreshold leakage due to AWL-VWL crosstalk
2. Electron migration and injection from aggressor channel to victim node
3. "Normal" leakage as time passes by

Access Pattern - RowHammer

Single-Sided - Case 2

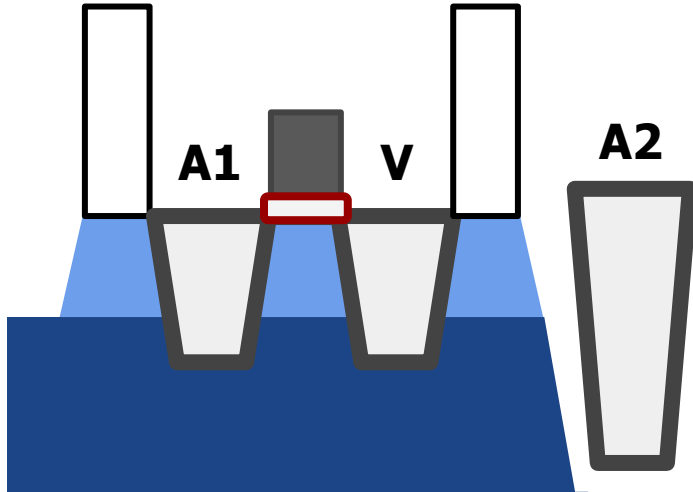


Contributing mechanisms

1. Increased subthreshold leakage due to AWL-VWL crosstalk (?)
2. Passing gate effect
3. "Normal" leakage as time passes by

Access Pattern - RowHammer

Double-Sided



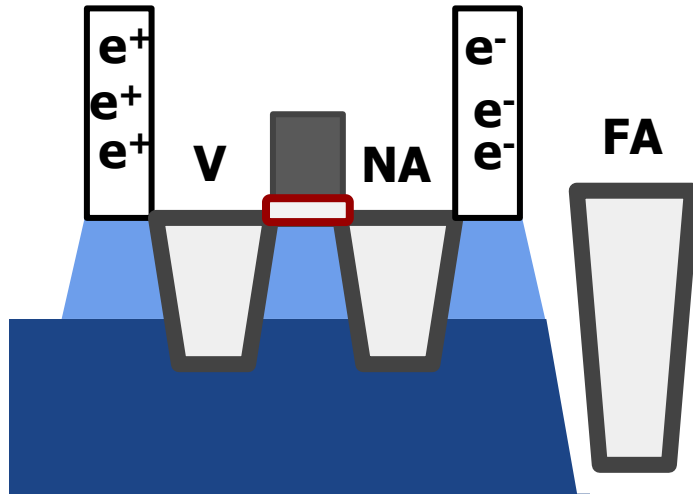
Contributing mechanisms

1. Increased subthreshold leakage due to AWL-VWL crosstalk
2. Electron migration & injection from A1
3. Passing gate effect from A2
4. "Normal" leakage as time passes by

Access Pattern - RowHammer

Half-Double

Many Far Aggressor (FA) activations followed by only a few Near Aggressor (NA) activations causes bitflips in the Victim (V)



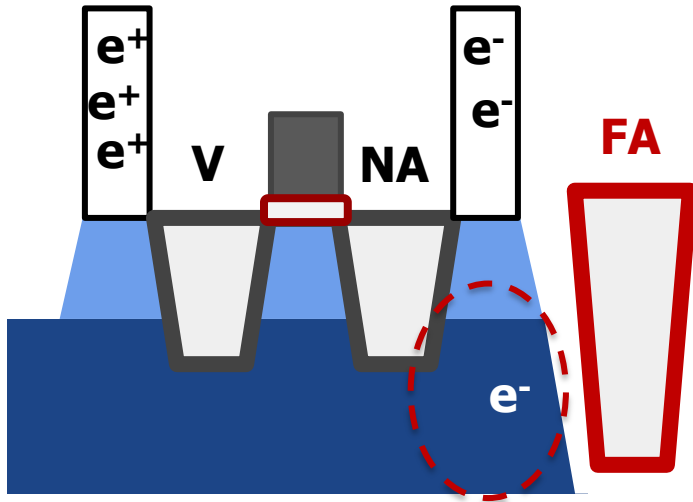
Hypothesized mechanisms

1. Frequent FA activation accumulates electrons near the NA side
2. Few NA activations causes those electrons to migrate and inject into V

Access Pattern - RowHammer

Half-Double

Many Far Aggressor (FA) activations followed by only a few Near Aggressor (NA) activations causes bitflips in the Victim (V)



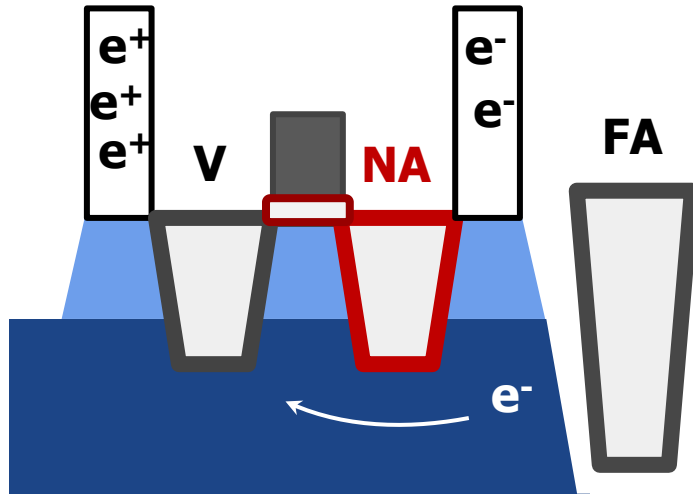
Hypothesized mechanisms

1. Frequent FA activation accumulates electrons near the NA side
2. Few NA activations causes those electrons to migrate and inject into V

Access Pattern - RowHammer

Half-Double

Many Far Aggressor (FA) activations followed by only a few Near Aggressor (NA) activations causes bitflips in the Victim (V)



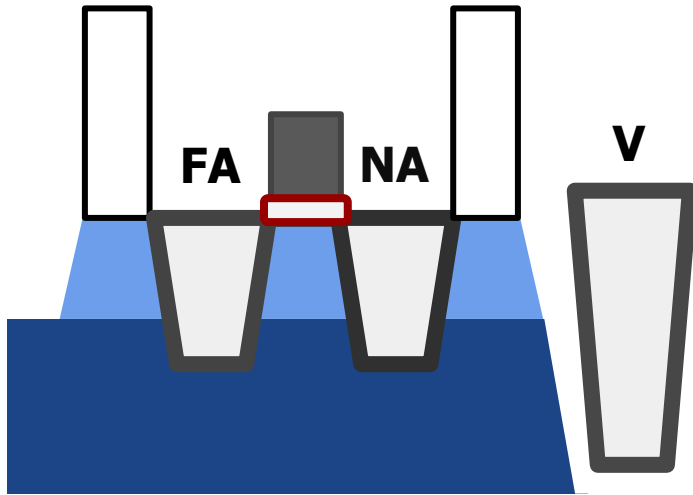
Hypothesized mechanisms

1. Frequent FA activation accumulates electrons near the NA side
2. Few NA activations causes those electrons to migrate and inject into V

Access Pattern - RowHammer

Half-Double

Another case...?



No hypothesized mechanisms so far...

Ongoing Works

ABACuS:

All-Bank Activation Counters for Scalable and Low Overhead RowHammer Mitigation

USENIX Security 2024

Ataberk Olgun
21.09.2023

Executive Summary

Problem: RowHammer vulnerability worsens as DRAM becomes denser

- Existing defenses become **more costly**
- Benign workloads **frequently** trigger **performance-degrading** RowHammer mitigations

Goal: Prevent RowHammer bitflips at **low performance, energy, and area cost**

Key Observation: Workloads tend to access **the same row in all DRAM banks** at around the **same time**

Key Idea: Use **one hardware counter** to keep track of activation counts of the **same row across all banks**

- Make high-performance, area-hungry counter-based mechanisms **practical**

Key Results: Memory system simulations using 62 single core and 62 8-core workloads

At all tested RowHammer thresholds (1000, 500, 250 125):

Faster than the **lowest-area-cost** counter-based defense mechanism

Smaller than the **lowest-performance-overhead** counter-based defense mechanism

0.59% avg. performance overhead (single-core) at a **future RowHammer threshold** (1K)

- Only 9.79 KiB **on-chip** storage per DRAM rank (0.02% of a Xeon processor)

1.52% avg. performance overhead (single-core) at an **ultra-low** threshold (125)

- 75.70 KiB **on-chip** storage per DRAM rank (0.11% of the Xeon processor)

RowHammer in HBM Chips (2023)

- Ataberk Olgun, Majd Osserian, A. Giray Yağlıkçı, Yahya Can Tugrul, Haocong Luo, Steve Rhyner, Behzad Salami, Juan Gomez-Luna, and Onur Mutlu, **"An Experimental Analysis of RowHammer in HBM2 DRAM Chips"**
Proceedings of the 53rd Annual IEEE/IFIP International Conference on Dependable Systems and Networks Disrupt Track (DSN Disrupt), Porto, Portugal, June 2023.
[[arXiv version](#)]
[[Slides \(pptx\)](#)] [[pdf](#)]
[[Talk Video](#) (24 minutes, including Q&A)]

An Experimental Analysis of RowHammer in HBM2 DRAM Chips

Ataberk Olgun¹ Majd Osseiran^{1,2} A. Giray Yağlıkçı¹ Yahya Can Tuğrul¹
Haocong Luo¹ Steve Rhyner¹ Behzad Salami¹ Juan Gomez Luna¹ Onur Mutlu¹
¹SAFARI Research Group, ETH Zürich ²American University of Beirut

Executive Summary

Motivation: HBM chips have new architectural characteristics (e.g., 3D-stacked dies) that might affect the RowHammer vulnerability in various ways

Understanding RowHammer enables designing effective and efficient solutions

Problem: No prior study demonstrates the RowHammer vulnerability in HBM

Goal: Experimentally analyze how vulnerable HBM DRAM chips are to RowHammer

Experimental Study: Detailed experimental characterization of RowHammer in a modern HBM2 DRAM chip. Our study provides two main findings:

1. Spatial variation of RowHammer vulnerability

- Different channels in a 3D-stacked HBM chip exhibit different RowHammer vulnerability
- DRAM rows near the end of a DRAM bank are more RowHammer resilient

2. On-DRAM-die RowHammer mitigations

- A modern HBM chip implements undisclosed on-DRAM-die RowHammer mitigation
- The mitigation refreshes a victim row after every 17 periodic refresh operations (e.g., similar to DDR4 chips)

Discover New Bitflips
Fundamentally Fix Them
To Build More Robust
Systems for Future