Circadian Rhythm: A Candidate for Achieving Everlasting Flash Memories

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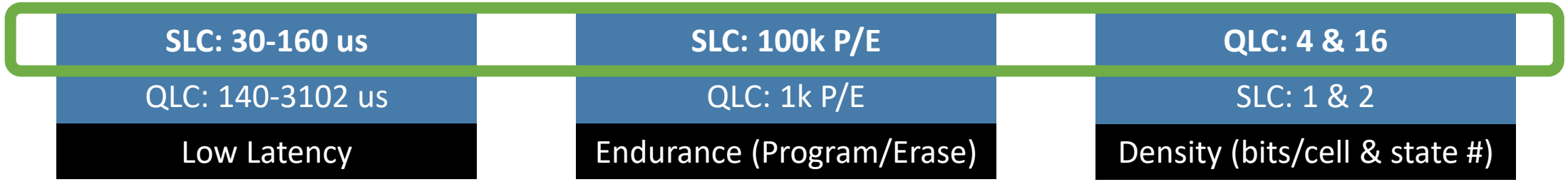
Reliability of FLASH

- Flash memories: dense, non-volatile, low latency, random access I/O
- Endurance limitation: wear-out by using (Program/Erase cycling)
- Reliability and Sustainability are important now more than ever

Problem



- Hybrid SSDs are proposed
  - Along with System-level mitigation techniques (over-provisioning, wear-leveling, read-retry, etc.)

Vacancy

- in Device-level: Passive and Accelerated Recovery for **temporary wearout**

Circadian Rhythm of Flash: preventing permanent wearout

Solution

hplp
High-Performance Low-Power

Yoo, Sangjin, and Dongkun Shin. "Reinforcement Learning-Based {SLC} Cache Technique for Enhancing {SSD} Write Performance." *12th {USENIX} Workshop on Hot Topics in Storage and File Systems (HotStorage 20)*. 2020.

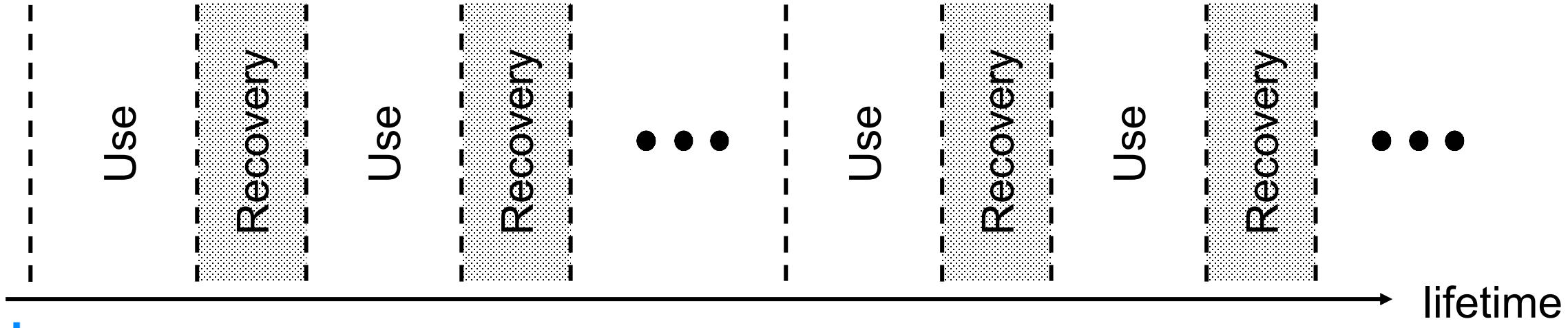
Circadian Rhythm of Flash

Circadian Rhythm of Human

- Sleep during the day not only at weekends

Circadian Rhythm for BTI and EM wearout*

Circadian Rhythm of Flash



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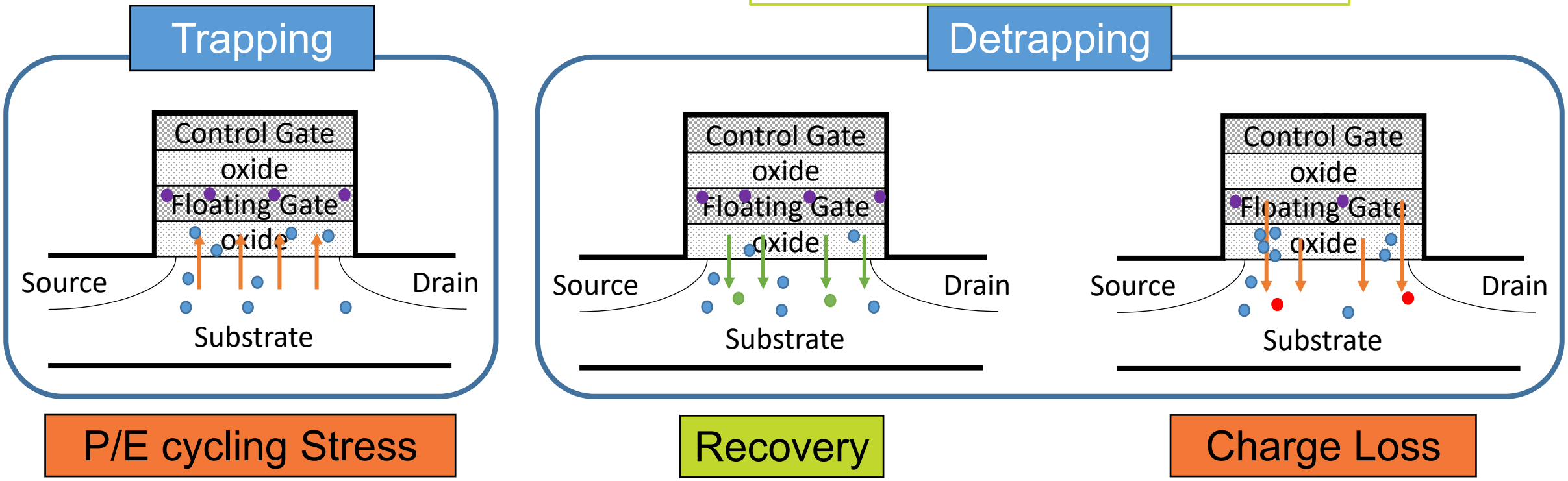
*Guo, Xinfei, and Mircea R. Stan. "Deep Healing: Ease the BTI and EM Wearout Crisis by Activating Recovery." 2017 47th Annual IEEE/IFIP International Conference on Dependable Systems and Networks Workshop (DSN-W). IEEE, 2017.

Use (Stress) and Recovery Mechanisms

- Electrons are forcibly moved during Programmed and Erase operations
- Recovery (detrapping) efficient for temporary traps.

$$A_F = \exp[(-E_{aa}/k)(1/T_{high} - 1/T_{low})]$$



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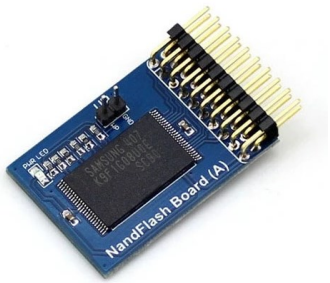
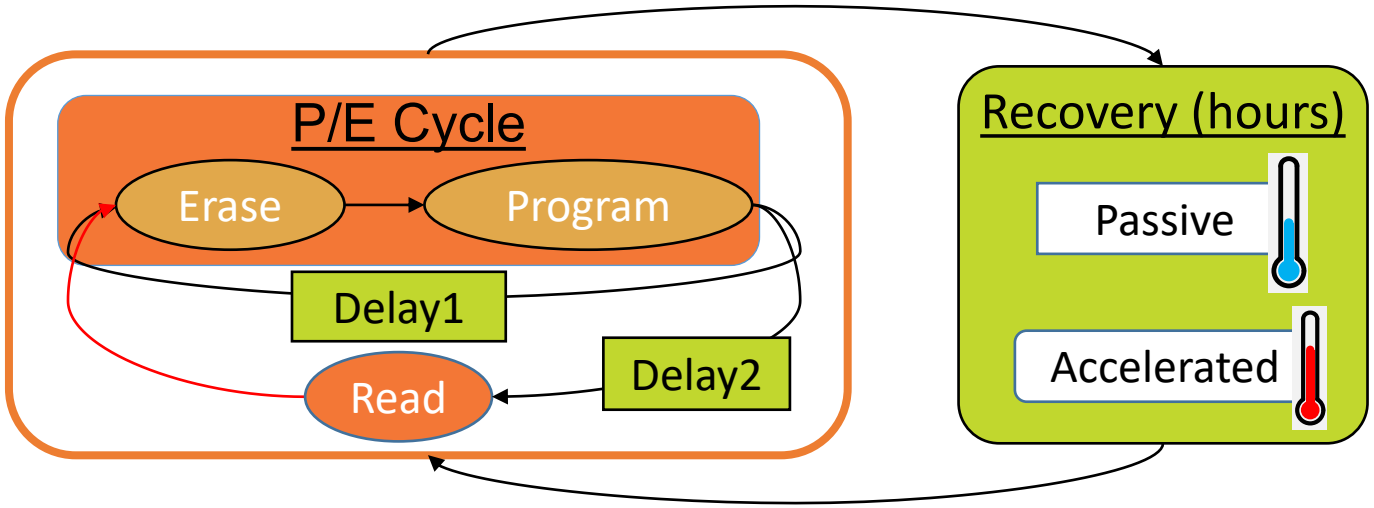
Circadian Rhythm prevents permanent wearout

Experimental Setup of Circadian Rhythms

- 21nm SLC NAND flash – floating gate transistor
- no-ECC during experiments and no read-retry
- 20 P/E Cycles + 1 Read
- temperature: 95 °C
- 7 different rhythms

ECC-1: 1 bit / (512+16 Byte)
ECC-4: 4 bit / (512+16 Byte)
$t_{delay1} = 1.5$ s (dwell time)
$t_{delay2} = 3$ s (retention time)





M. C. Morgul, M. N. Sakib and M. Stan, **Reliable Processing in Flash with High Temperature.** The IEEE International Integrated Reliability Workshop (IIRW) 2021, October 4-29, 2021
https://www.waveshare.com/nandflash-board-a.htm

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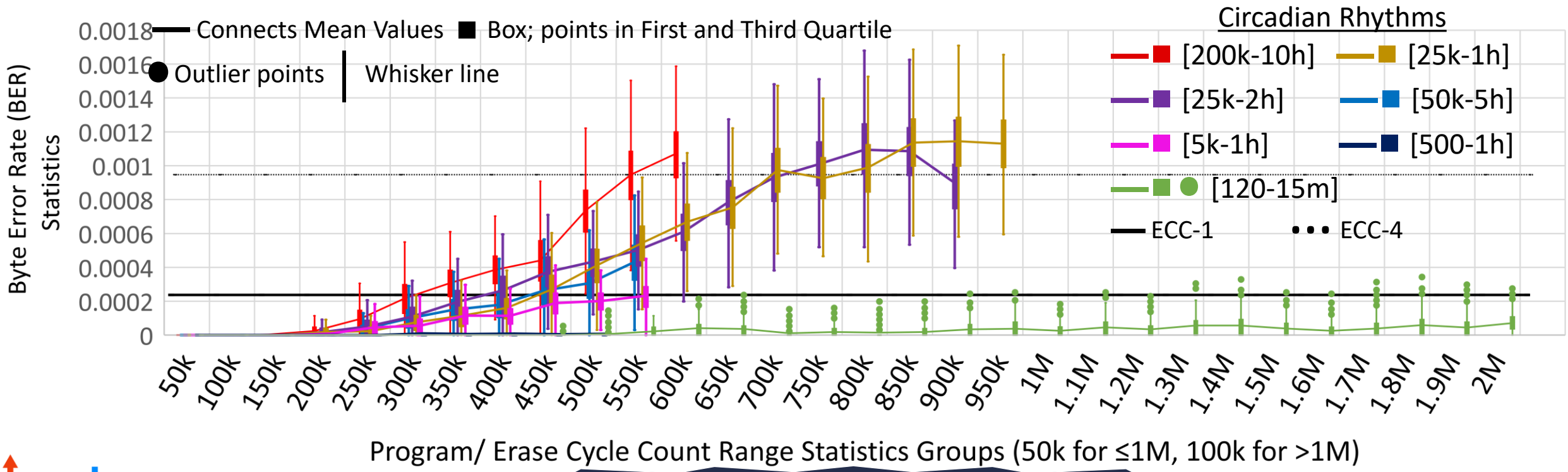
Circadian Rhythm on Prevention of Permanent Wearout

- The rhythm of [120-15m] (i.e., 120 P/E cycles followed by 15 min of recovery) , compared to [200k-10h].
  - **increases** lifetime with ECC-1 **2.9x**; but only 60 times exceed ECC-1 till **1.95M**, which actually means **9x improvement**
  - **decreases** the slope of linear fit **by 70x** – flattens the trend



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"Everlasting" Flash! or about to be…

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Circadian Rhythm	BER = ECC-1	Lifetime Improvement	Slope in Linear Fit	
200k-10h	*223k*	*baseline*	1.2e-9	1x
25k-1h	245k	9.8%	1.6e-9	1.27x
25k-2h	230k	3.1%	1.6e-9	1.27x
50k-5h	264k	18.3%	8.5e-10	2.34x
5k-1h	294k	31.8%	5.1e-10	3.89x
500-1h	**w.r.t. values @482k**	**285.6%**	**2.2e-11**	**90.45x**
120-15m	**858k**	**284.7%**	**2.7e-11**	**73.70x**

This is translated into **9x**

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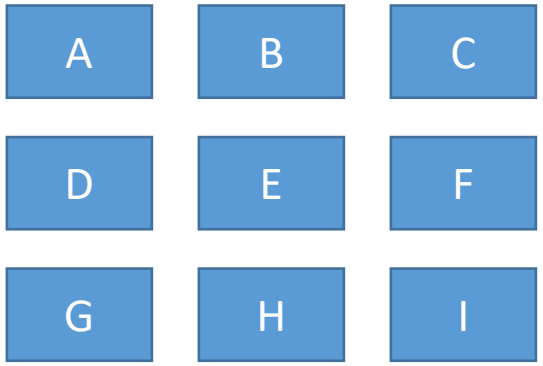
Worst Case: High Utilization Demanding Application

- An application that requires to access all the bits (capacity) at any time
  - Tremendous amount of parallelism: as high as number of bits
  - Example: Processing in-memory
- With just **4x (5-1) more capacity**, **8x (9-1) more lifetime** is gained [120-15m]
- Overall more than **2x sustainability improvement** when you consider total cost of ownership



8 times replacements

	Time:	3.75m	3.75m	3.75m	3.75m	3.75m
0	$Block_0$	*Use*	*Recov*	*Recov*	*Recov*	*Recov*
1	$Block_1$	*Recov*	*Use*	*Recov*	*Recov*	*Recov*
2	$Block_2$	*Recov*	*Recov*	*Use*	*Recov*	*Recov*
3	$Block_3$	*Recov*	*Recov*	*Recov*	*Use*	*Recov*
4	$Block_4$	*Recov*	*Recov*	*Recov*	*Recov*	*Use*

9x lifetime but 4x more capacity

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Summary

- Existing recovery methods at **the device-level** left the **irreversible** component of wearout **uncheck**
- Circadian Rhythm **prevents** the occurrence of most of the **permanent wearouts**
- Experimental results of SLC floating gate shows that **[120-15m] Circadian Rhythm** increases lifetime of flash memory by **9x**
- Circadian Rhythm improves **sustainability** at least **2x** even in the hypothetical worst-case

Discussion and Future Work

- Circadian Rhythm is the key to unlock "**everlasting**" flash memories
- Study* shows Circadian Rhythm (CR) is up to **100% beneficial** for **Bias Temperature Instability** wearout of FETs and **ElectromMigration**
- Therefore, Circadian Rhythm recovery approach can be **generalized to all electronics**
  - Such as to other non-volatile memories; ReRAM, FeRAM, memristors etc.

Future works:

- Repeating experiments for other flash technologies (i.e. **charge-trap, MLC/TLC/QLC, 3D etc.)**
- Augmenting **FTL** (Flash Transition Layer) that exploits CR
- Developing **al-in-one** approach that synchronizes CR for a complete system

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