Flash Firmware Secrets Revealed

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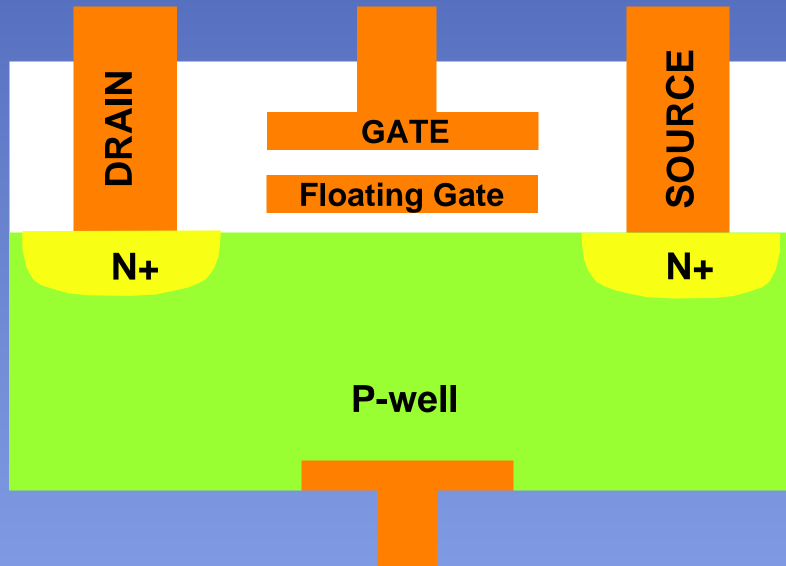
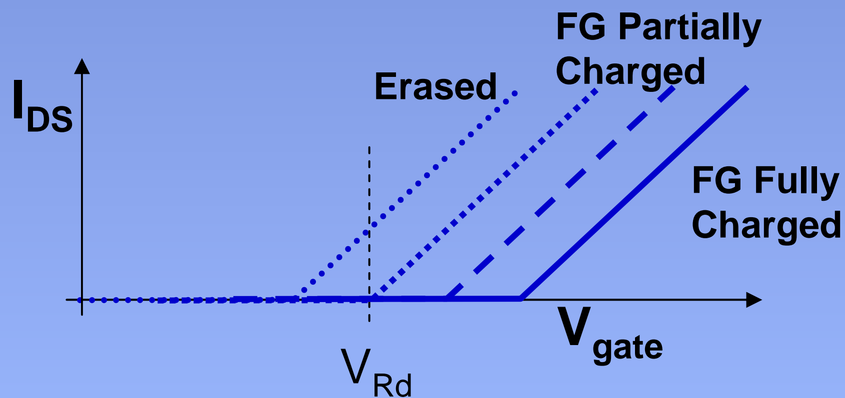
Flash Memory SUMMIT

Overview

- Objective is to use NAND flash beyond its guaranteed life by exploiting knowledge of failure mechanisms.
- Program Erase Cycling and Read Disturbs can cause excessive error rate.
  - Goal: model error rate degradation as a function of both PE cycles & read disturbs so that firmware can optimally wear level.
  - With accurate modeling of block life, it is possible to improve the choice of block to recycle.
- The focus of this presentation is on improving models of PE & read disturb effects through measured data.

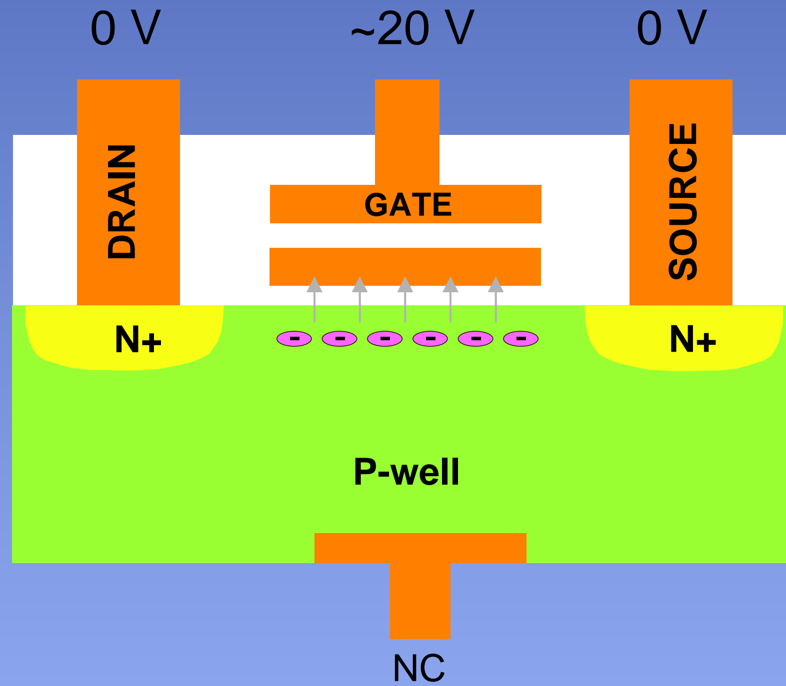
Floating Gate NAND Cell





- Charge on floating gate is trapped by the surrounding insulator.
- V_{TH} shifts to a higher voltage in proportion to the amount of charge trapped on the floating gate.

Programming



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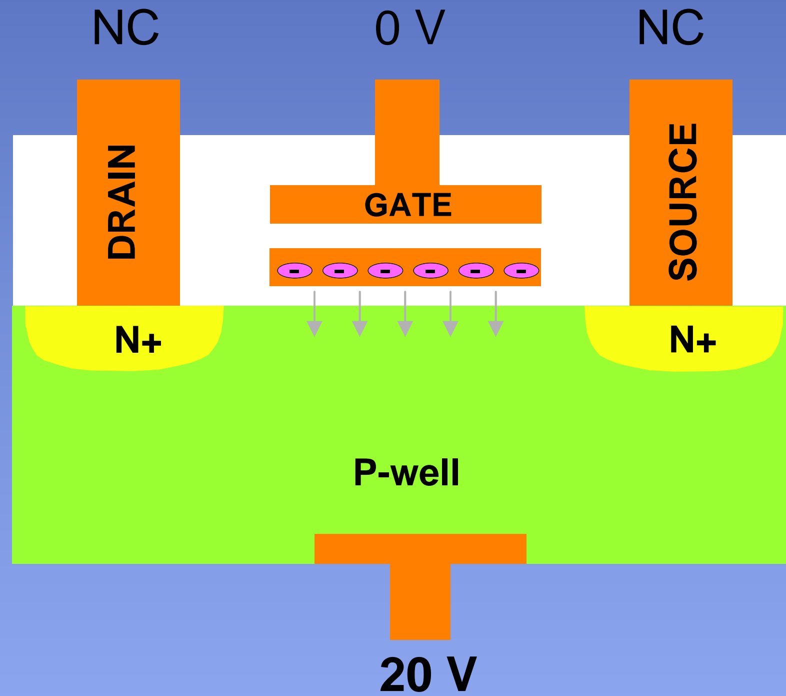
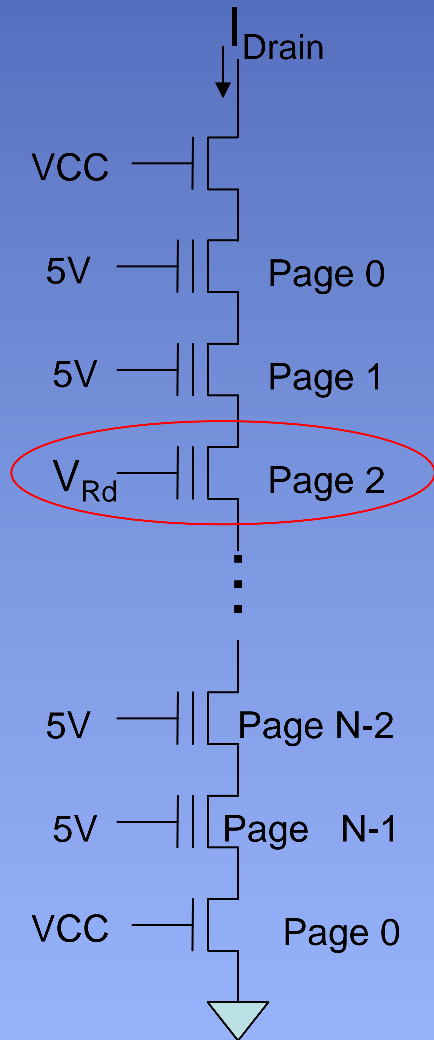
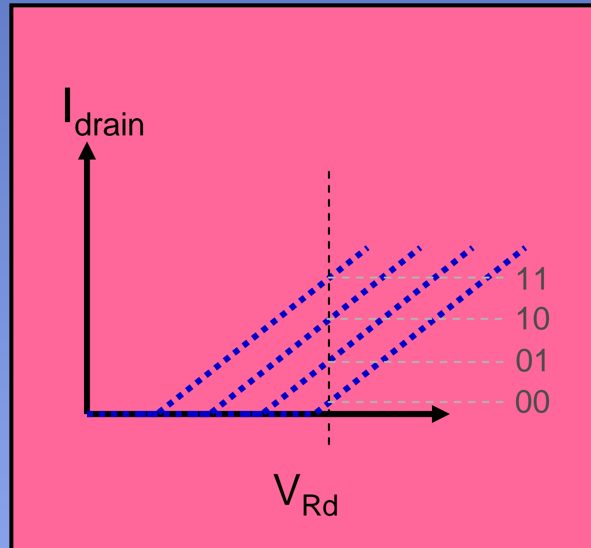
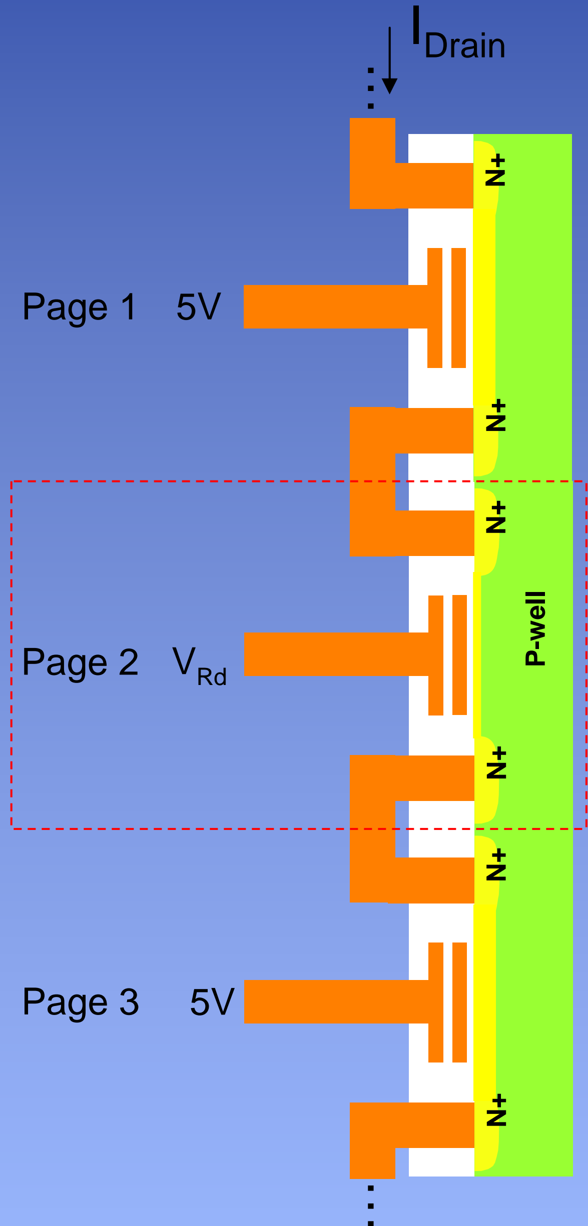
Erasing



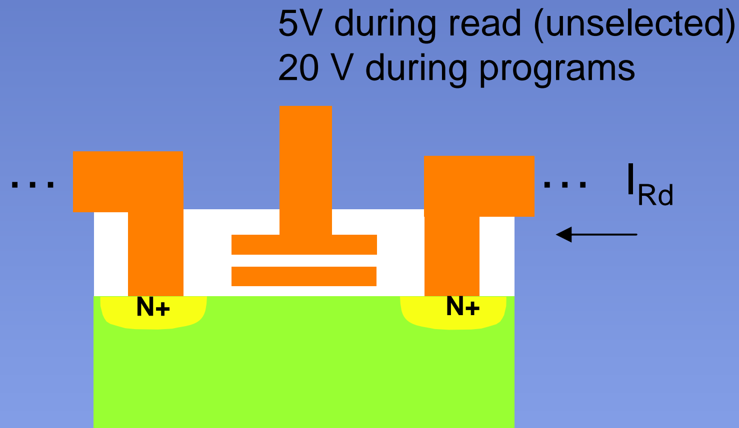
Reading







Read Disturbs



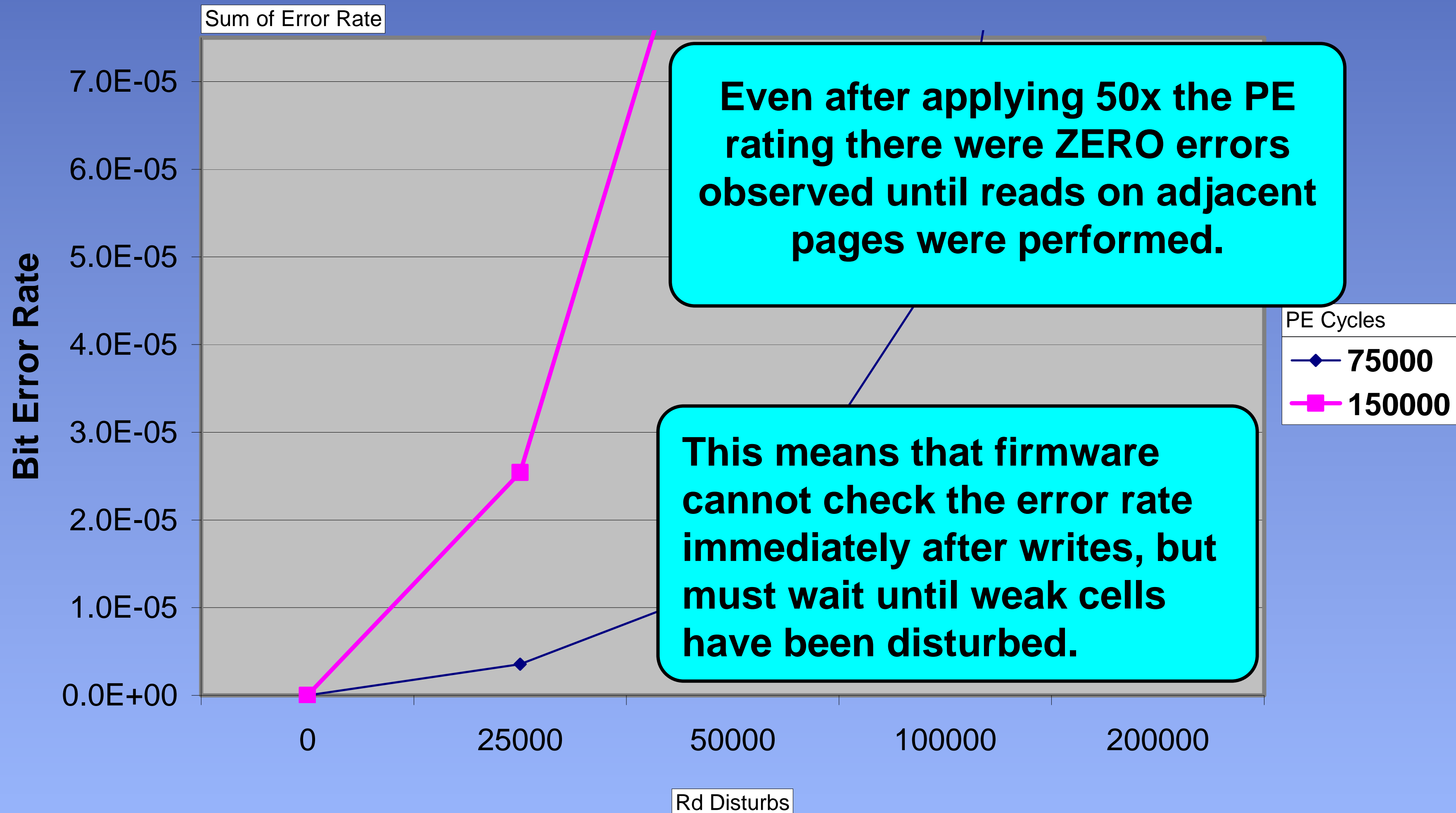
- Unselected cells receive a voltage that mimics a low voltage program.
- The relative size of the energy barrier that keeps electrons from populating the floating gate is lowered during reads.
- Program / Erase cycles damage the insulator, thus lowering the energy needed to transfer electrons to the FG.

Experiment

- PE Loop
  - Apply N Program / Erase cycles (50% 1's, 50% 0's)
  - Rd Disturb Loop
    - Write all pages once
    - Apply K Reads to pages 2-5
    - Read all pages except 2-5 once, then report error rate
  - End Rd Dist Loop
- End PE Loop

- Results reported here are at room temperature.
- Data shown here is from a single chip
- PE rating is nominally 3000 cycles for this design.

BER without Read Disturbs



Program Erase Results

Rd Disturbs | 100000

Avg BER PE Cycle & Block Number

Average of BER

Large amount of lifetime variability across blocks

BER

3.0E-03
2.5E-03
2.0E-03
1.5E-03
1.0E-03
5.0E-04
0.0E+00

3000 6000 9000 12000 15000 18000 21000 24000 27000 30000 33000 36000 39000 42000 45000 48000 51000 54000 57000 60000 63000 66000 69000 72000

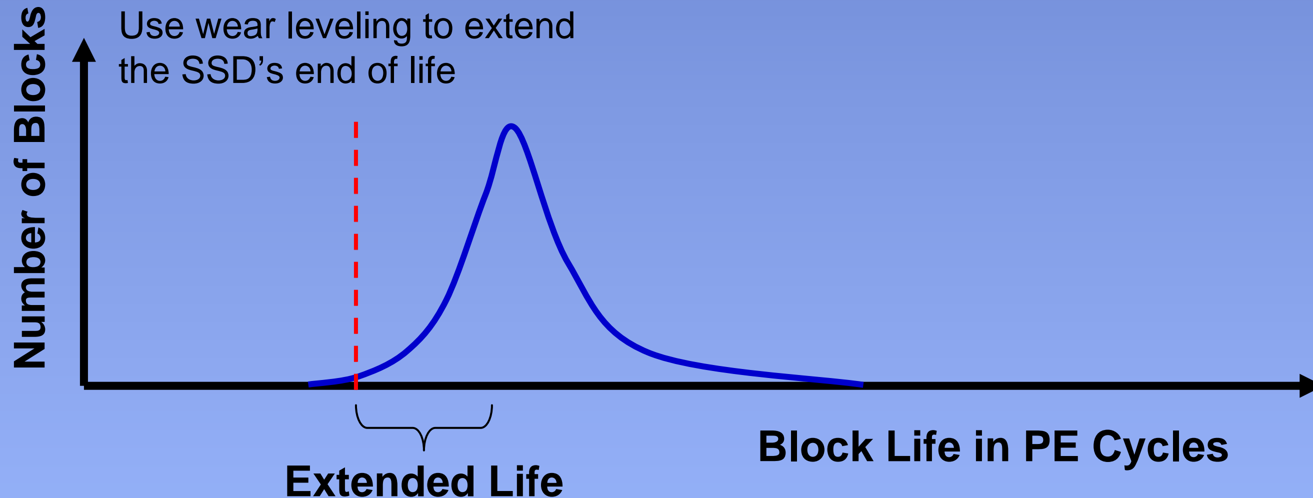
PE Cycles

Block
14
15
16
17
18
19
20
21
22
130
243
356
469
582
695
808
921
1034
1038
1039
1040
1147
1260
1373
1486
1599
1712
1825
1938
2049

Note: 100k reads means 100k reads/page on pages 2-5.

Block Lifetime and Wear Leveling

- If some blocks have substantially more life than others, the healthy blocks can be used more frequently to extend the life of the flash beyond the minimum.



Block BER vs Number of PE Cycles

Rd Disturbs	100000

Avg BER vs Number of and PE Cycles and Read Disturbs

Average of BER

BER: 1.0E-02, 1.0E-03, 1.0E-04, 1.0E-05, 1.0E-06

PE Cycles: 6000, 9000, 12000, 15000, 18000, 21000, 24000, 27000, 30000, 33000, 36000, 39000, 42000, 45000, 48000, 51000, 54000, 57000, 60000, 63000, 66000, 69000, 72000

Total BER spread at end of life > 40x

Total BER spread at "beginning" of life = 3.5x

Block: 13, 14, 15, 16, 17, 19, 20, 21, 22, 130, 243, 356, 469, 582, 695, 808, 921, 1034, 1038, 1039, 1040, 1147, 1260, 1373, 1486, 1599, 1712, 1825, 1938, 2049, 2062, 2063, 2064

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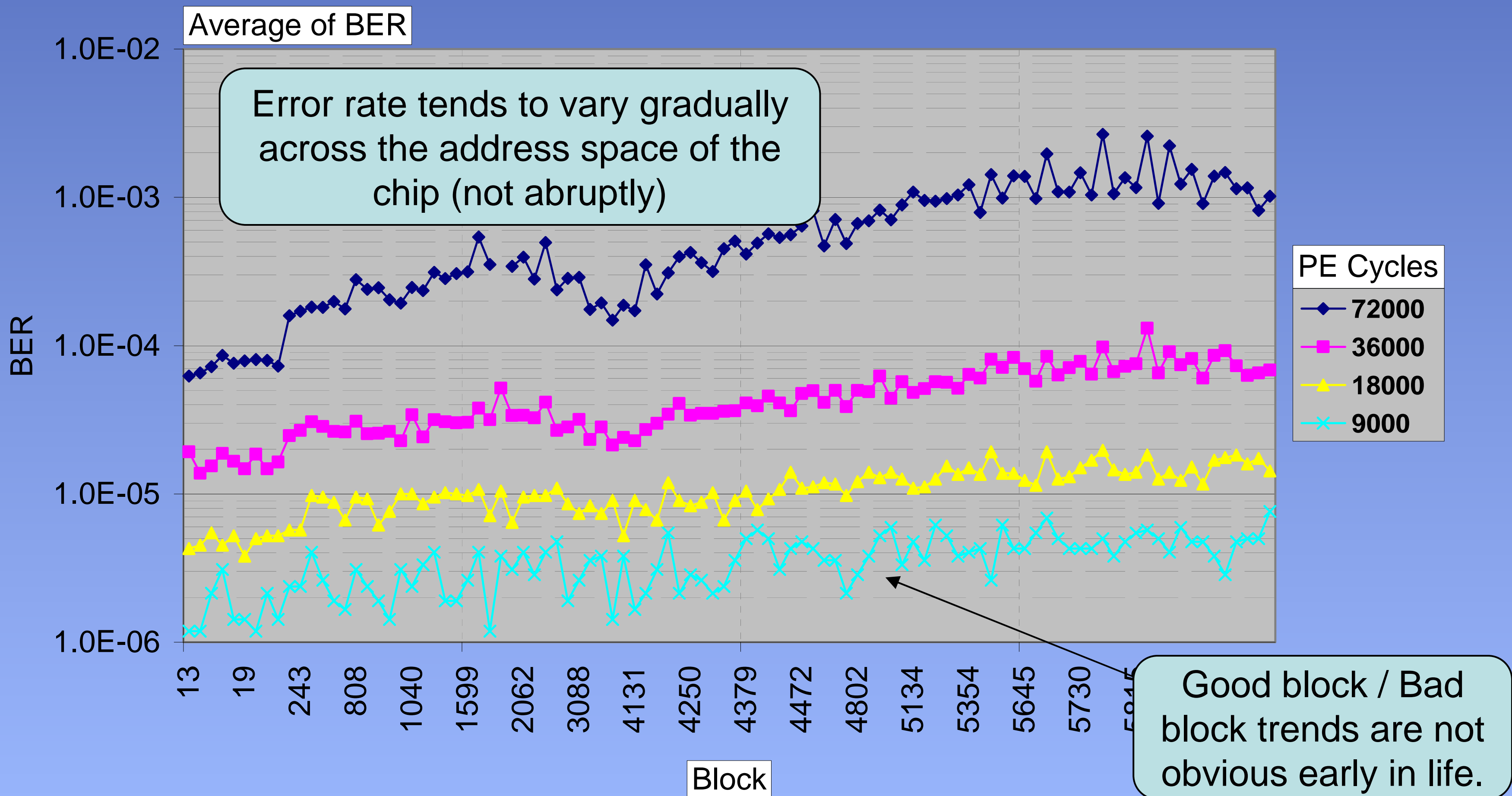
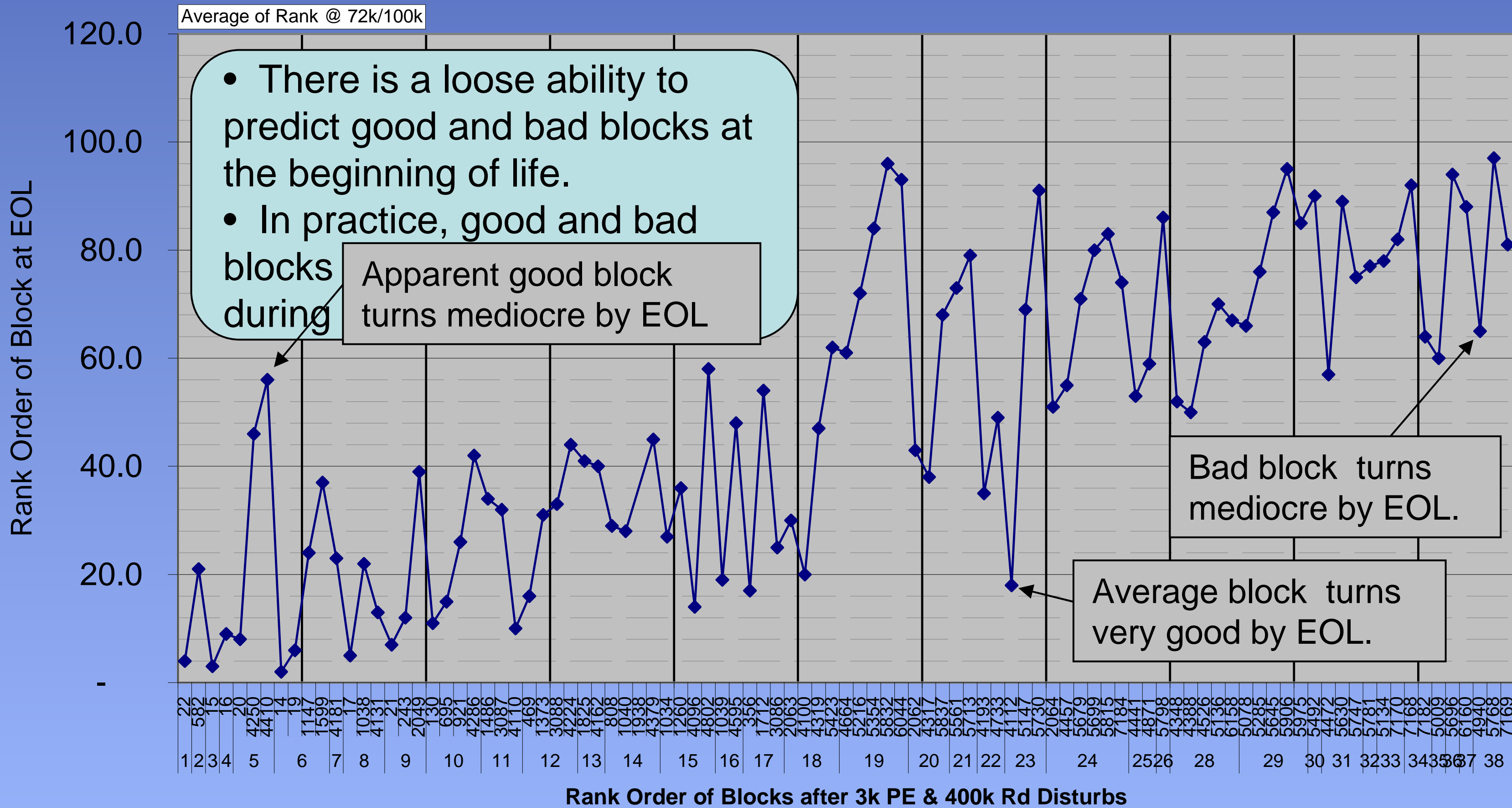
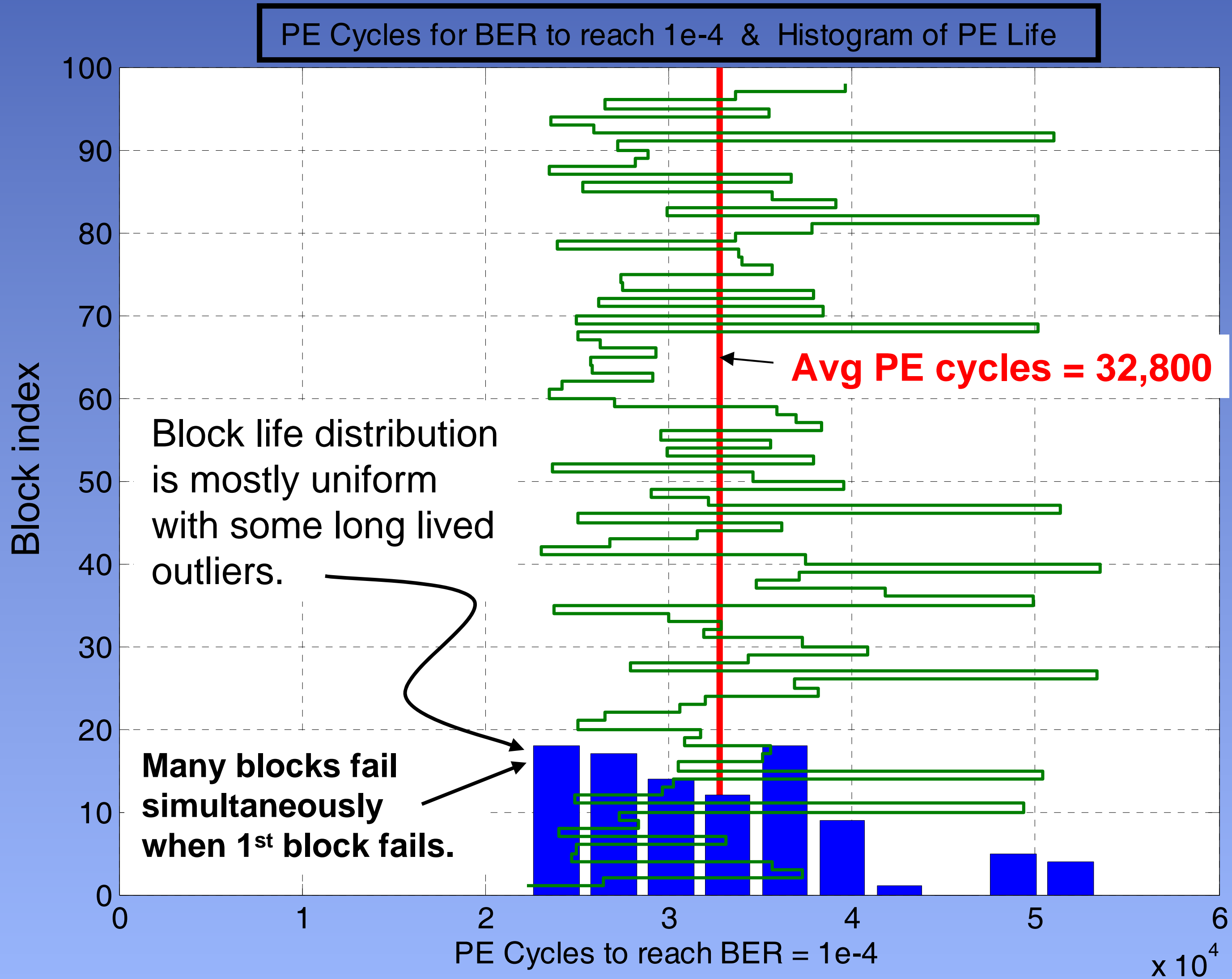
Variability in Block Aging



Predicting Block Life

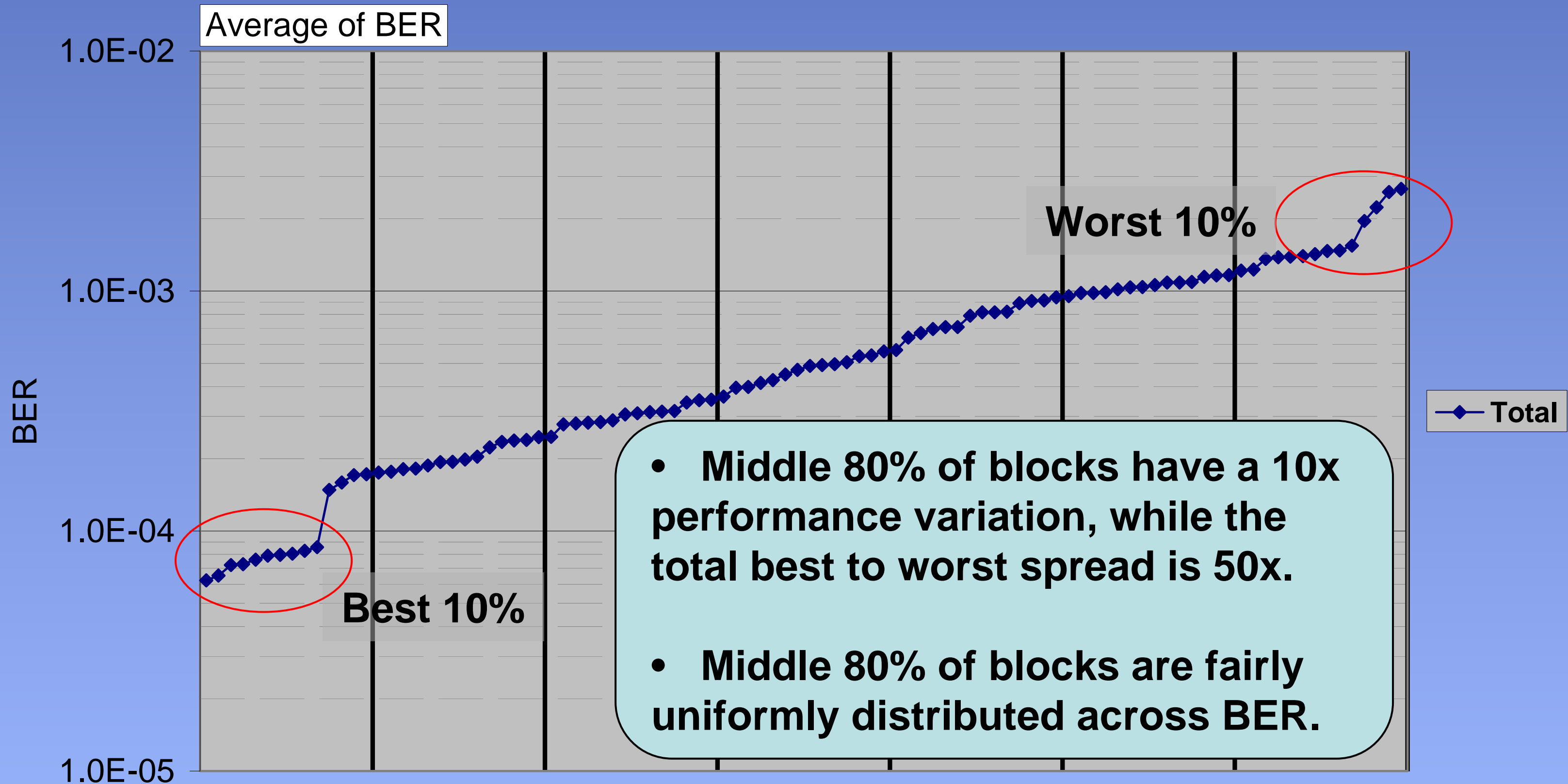


Distribution of Block Life (after 200k Reads)

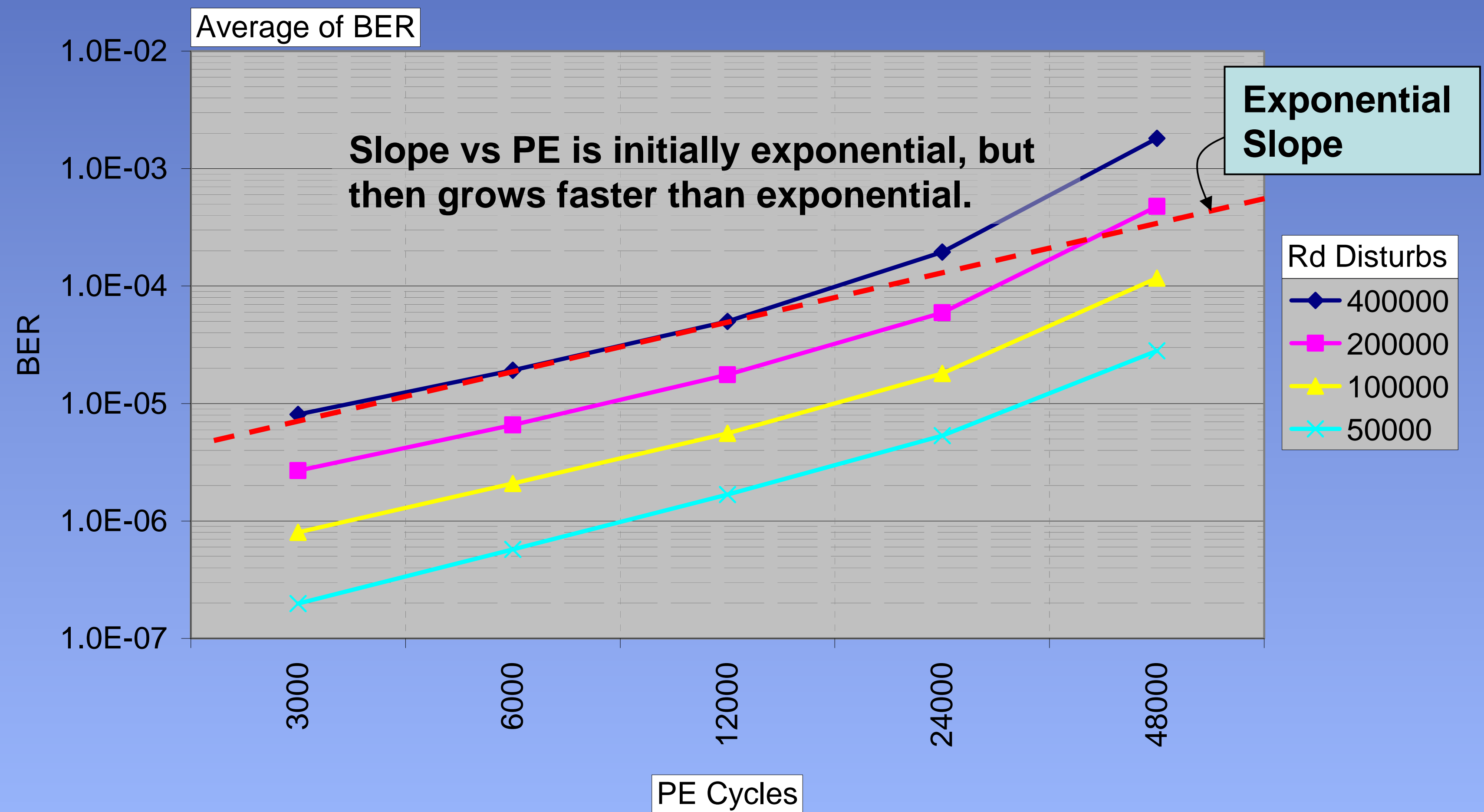


Sorted BER for 72k PE / 100k Rds

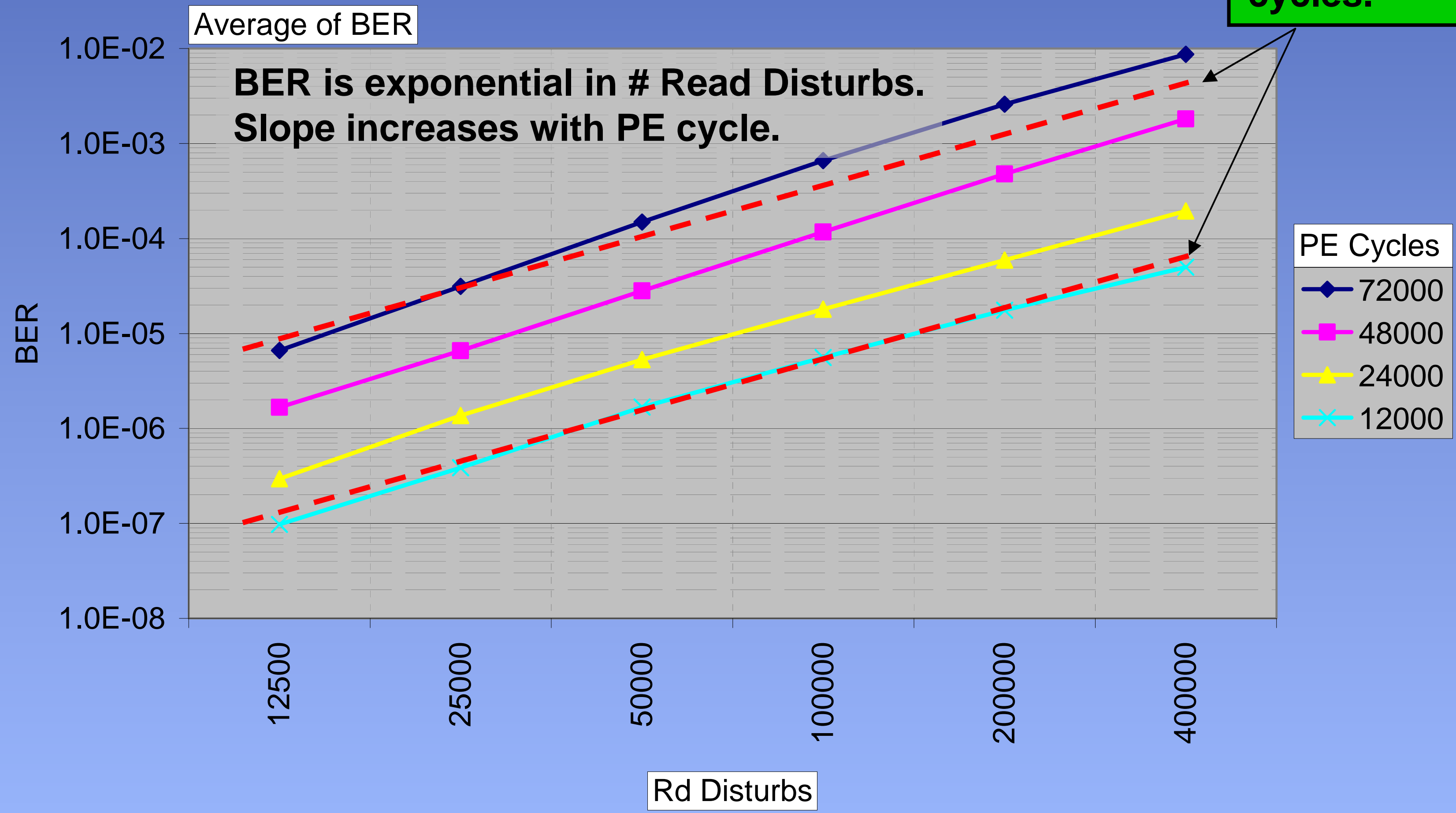
PE Cycles	72000	Rd Disturbs	100000



BER vs PE & Read Disturbs

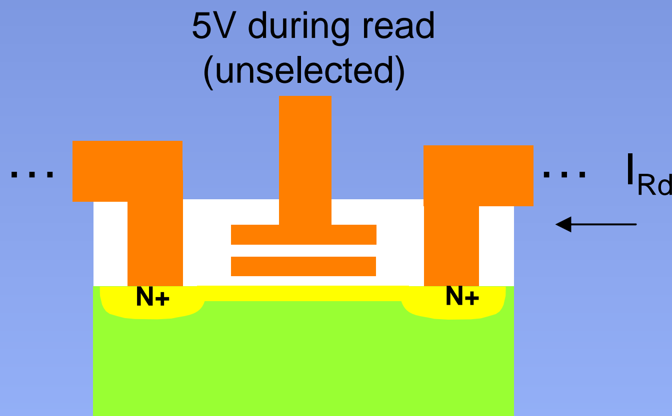


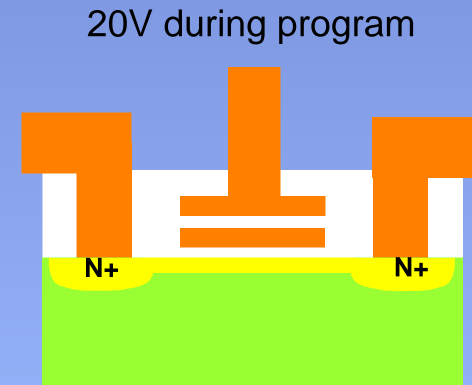
BER vs Read Disturbs & PE Cycles



Arrhenius Modeling

- Read disturbs behave as if each read of an adjacent page provides an opportunity for electrons to exceed the energy barrier needed to get to the floating gate.
- Increasing PE cycles causes the "activation energy" to increase and accelerate the effects of read disturbs.





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Summary

- Simple Model for Wear
  - BER is exponential vs the number of read disturbs
  - BER grows faster than exponential vs the number of PE cycles.
- Block Life
  - Predicting block life from early life measurements captures trends, but misses many exceptional blocks.
  - Block performance is generally well correlated with adjacent block performance.