Flash Secrets Revealed

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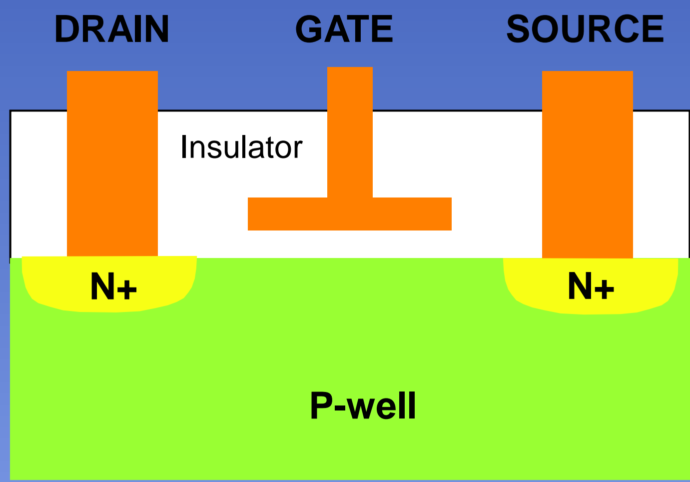
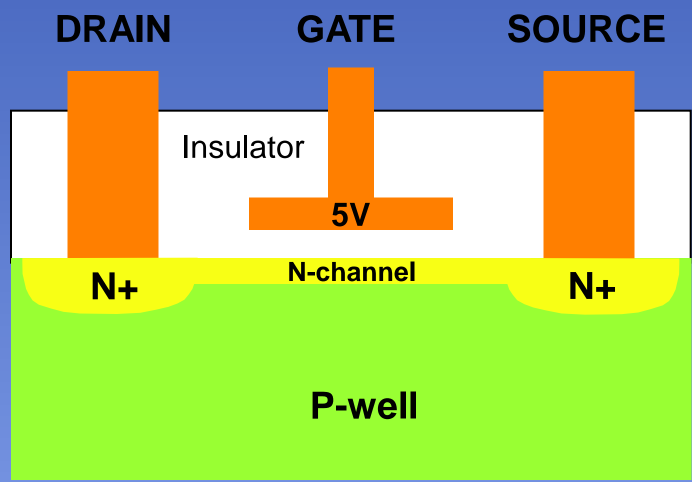
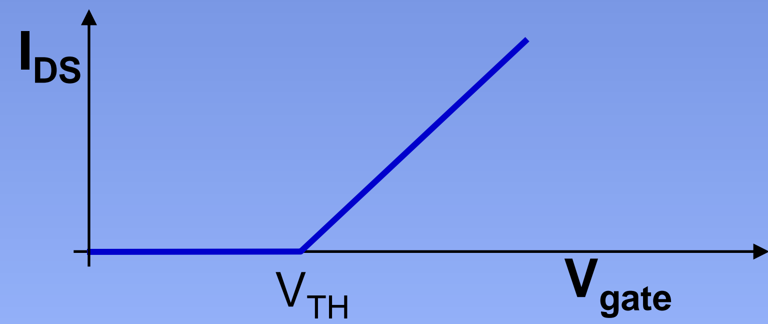
San Jose, CA

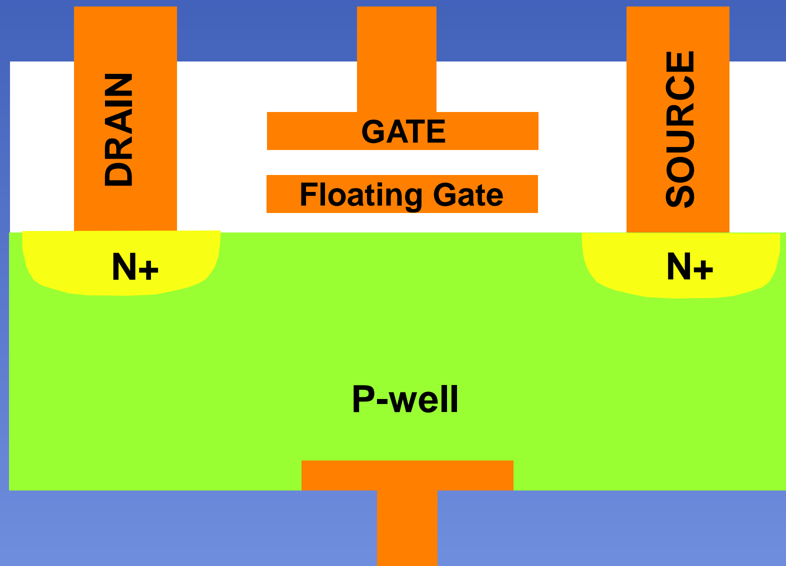
MOSFET

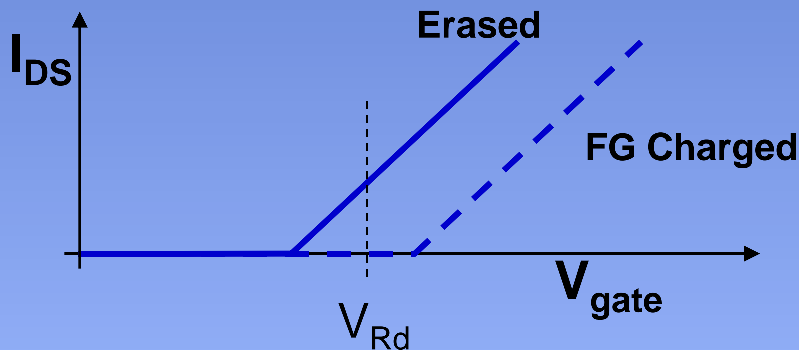






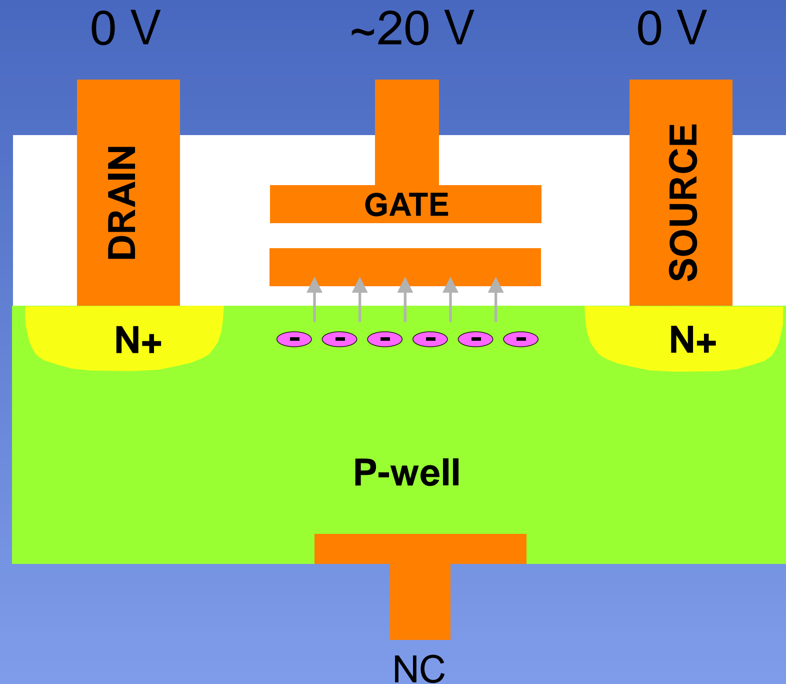
Floating Gate NAND Cell



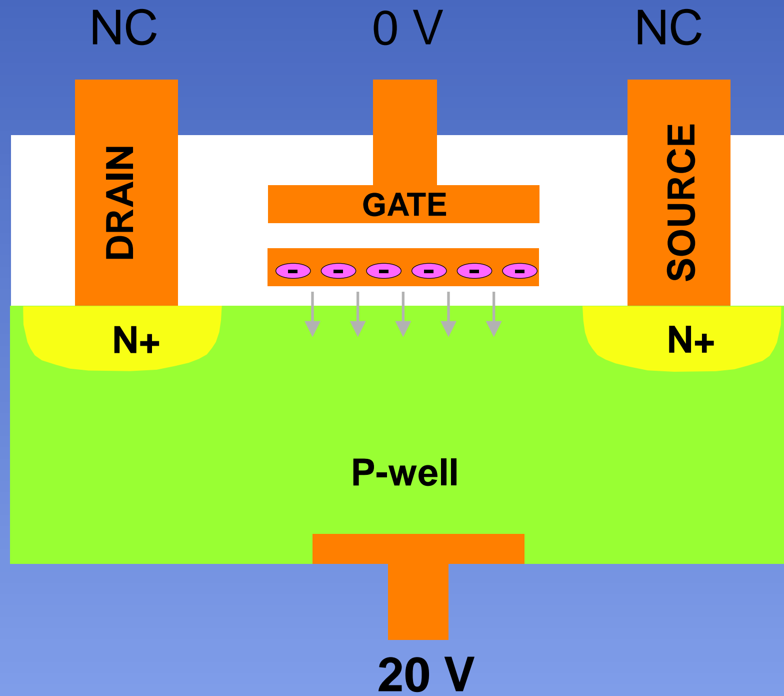


- Charge on floating gate is trapped by the surrounding insulator.
- V_{TH} shifts to a higher voltage in proportion to the amount of charge trapped on the floating gate.

Programming



Erasing



Reading

I_{Drain}

VCC

5V Page 0

5V Page 1

V_{Rd} Page 2

5V Page N-2

5V Page N-1

VCC Page 0

I_{drain}

11
10
01
00

V_{Rd}

I_{Drain}

Page 1 5V

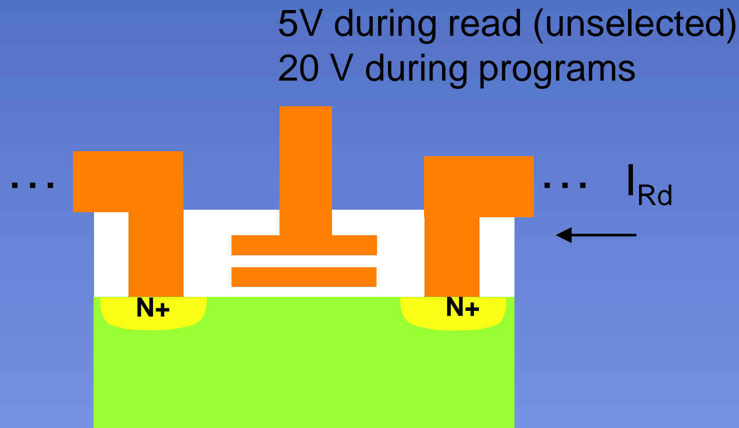
Page 2 V_{Rd}

Page 3 5V

N+

P-well

Read Disturbs



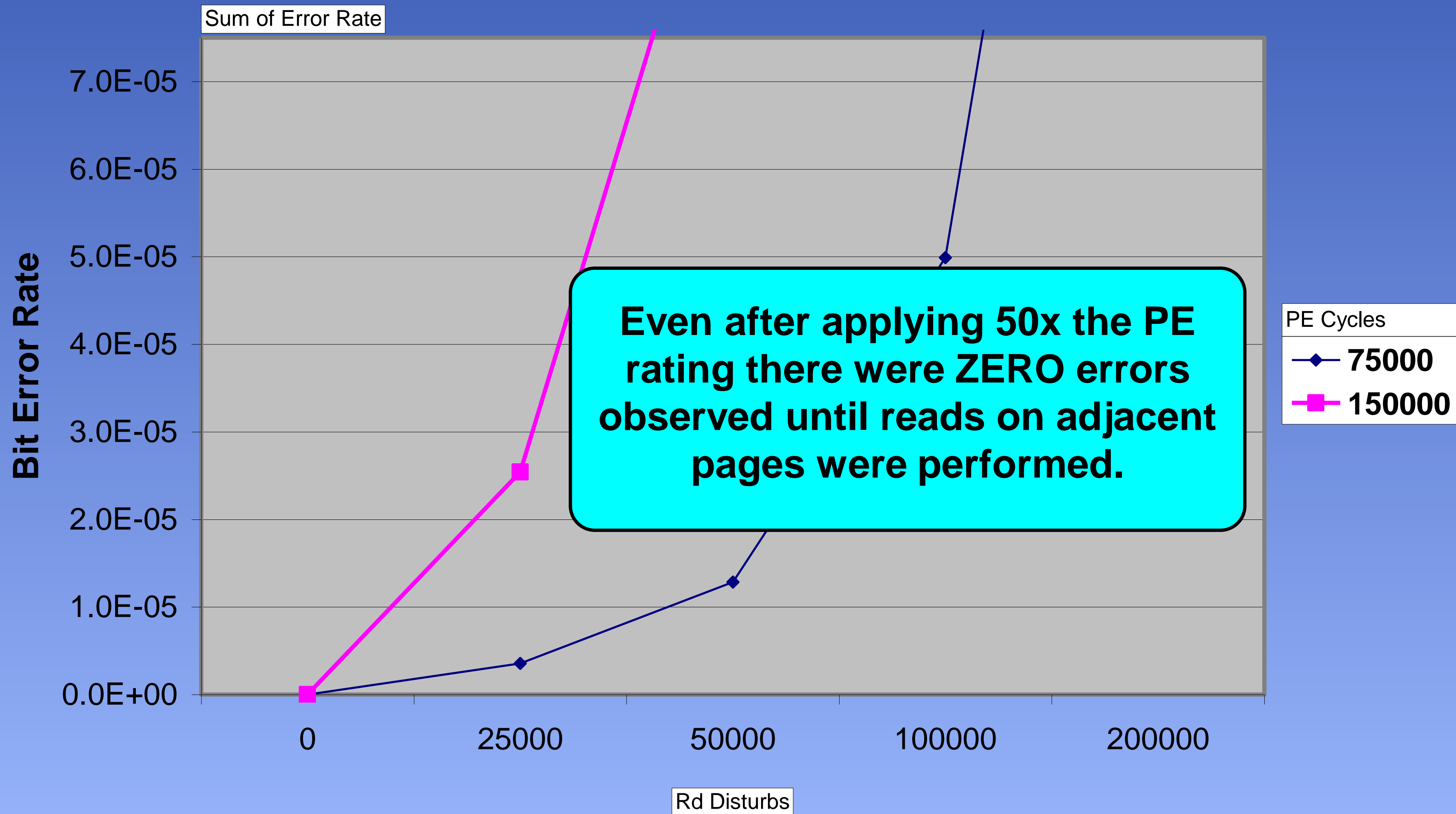
- Unselected cells receive a voltage that mimics a low voltage program.
- The relative size of the energy barrier that keeps electrons from populating the floating gate is lowered during reads.
- Program / Erase cycles damage the insulator, thus lowering the energy needed to transfer electrons to the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

Flash Memory

Rd Disturbs	100000

Avg BER PE Cycle & Block Number

Average of BER

Large amount of 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

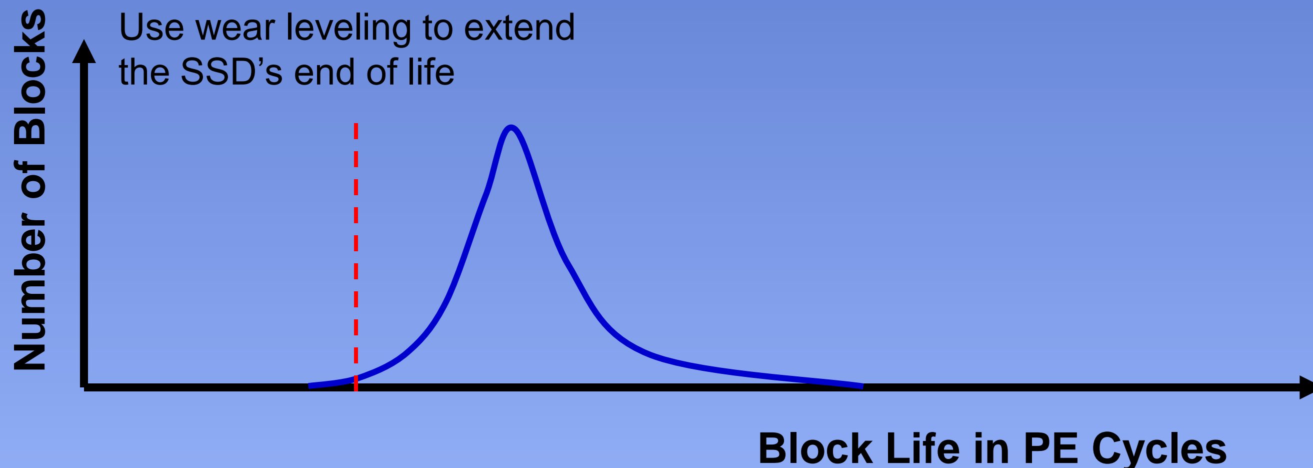
PE Cycles

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

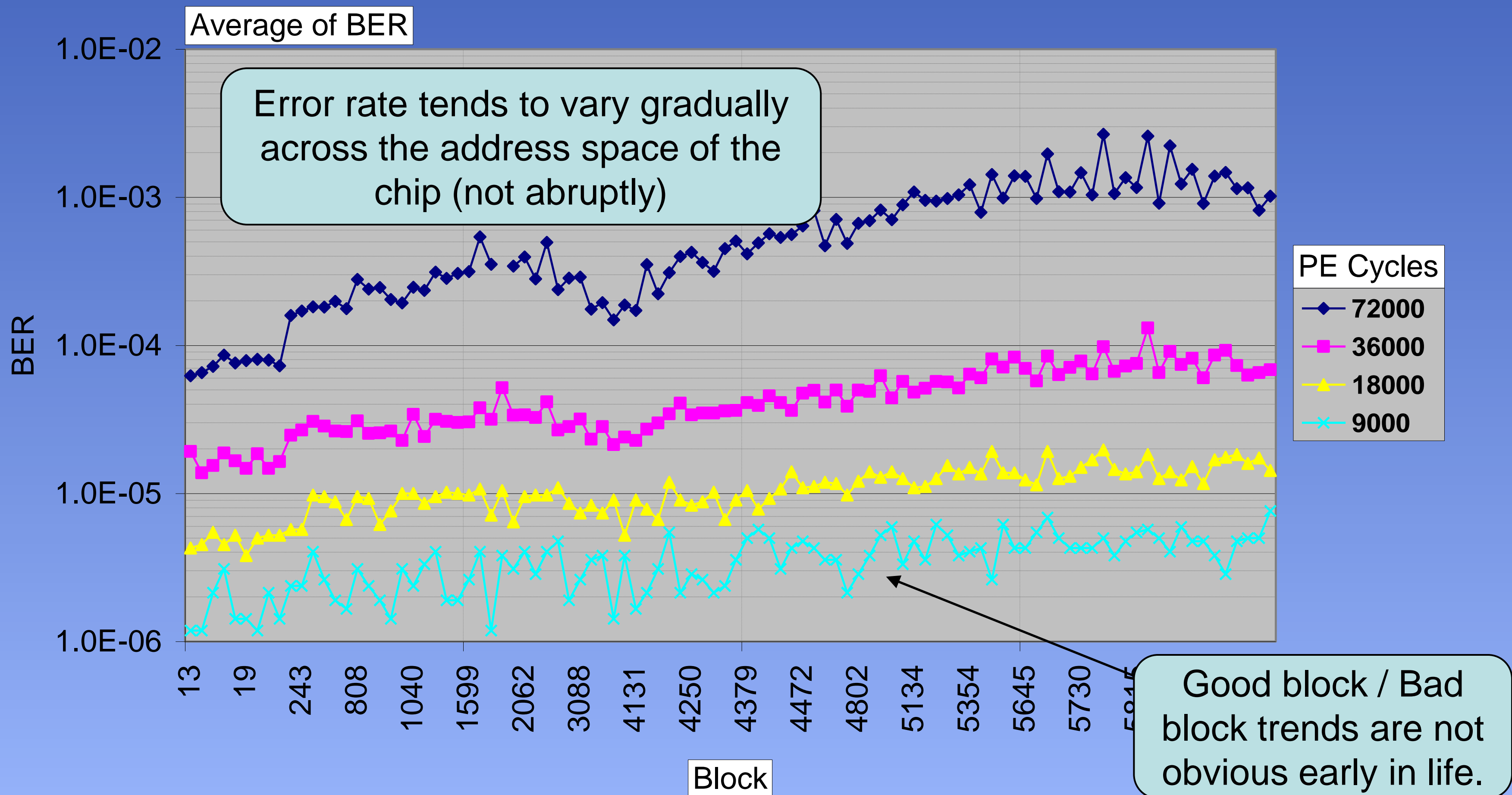
Block: 13, 14, 15, 16, 17, 19, 20, 21, 22, 130, 243, 356, 469, 582, 695, 808, 921, 1034, 1038, 1039, 1040, 1147, 1260, 1373, 1486, 1599, 1712, 1825, 1938, 2049, 2062, 2063, 2064

Flash Memory

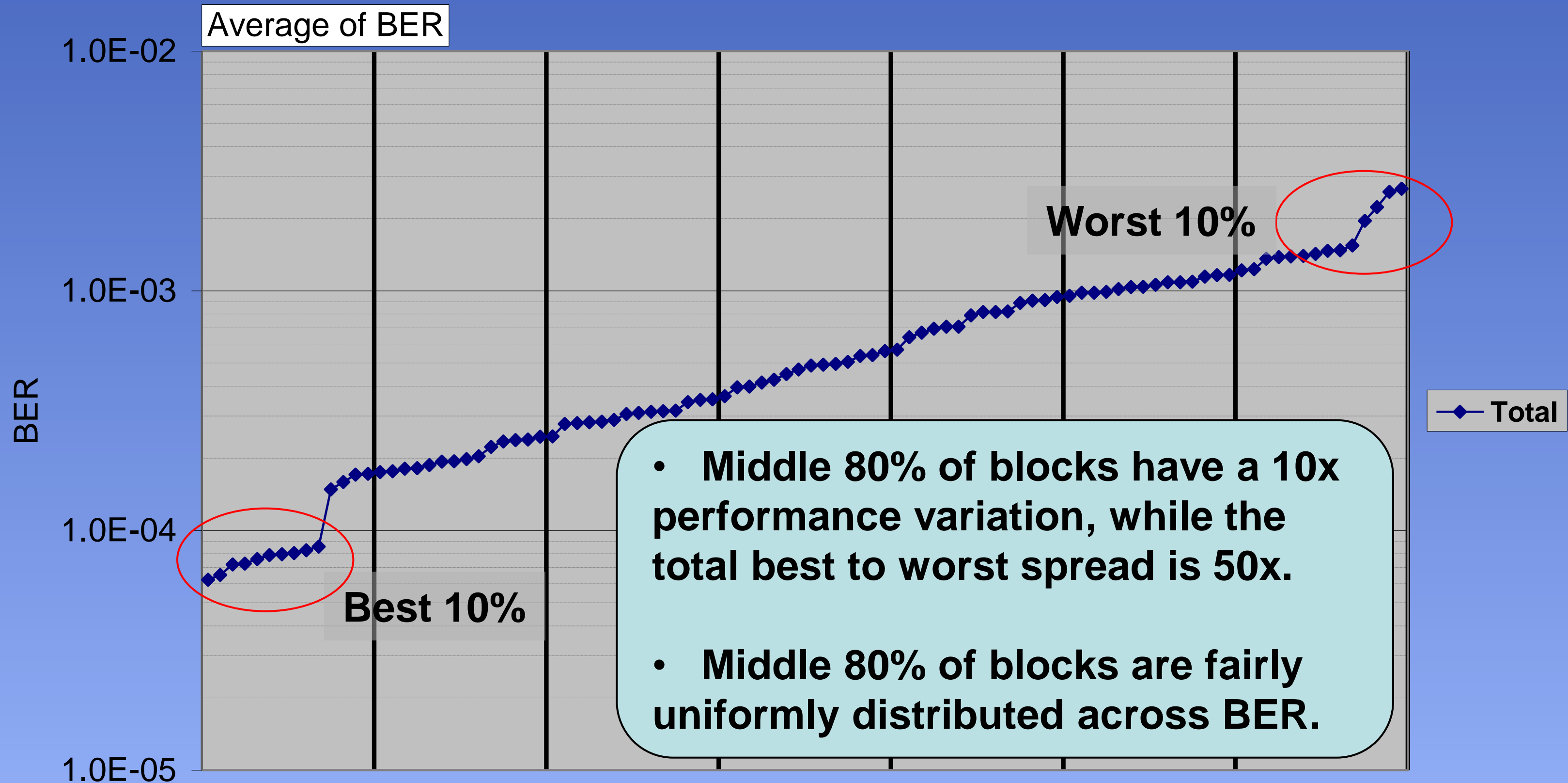
Variability in Block Aging

Rd Disturbs	100000

BER vs Block Number and Number of PE Cycles

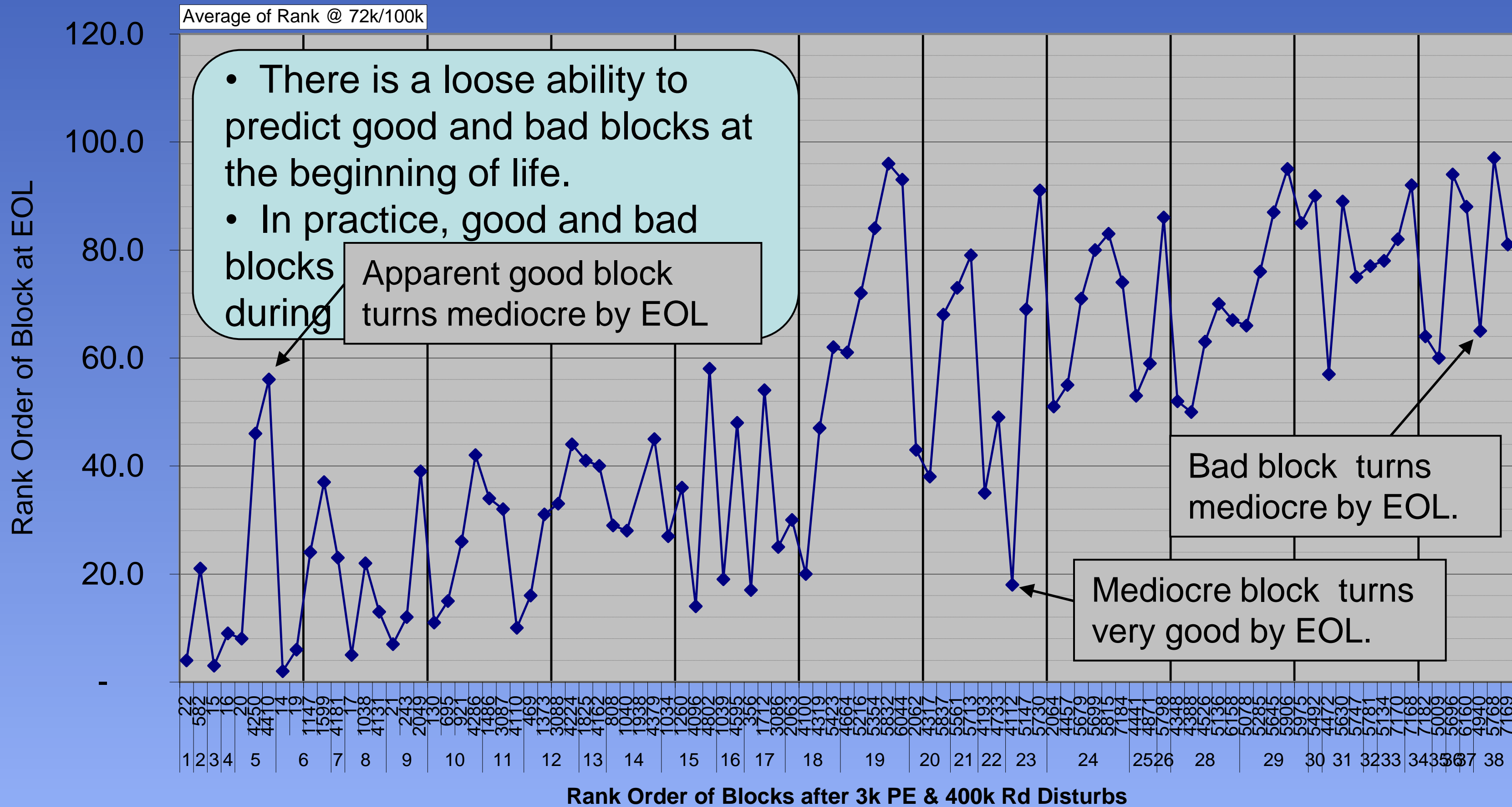


Sorted BER for 72k PE / 100k Rds

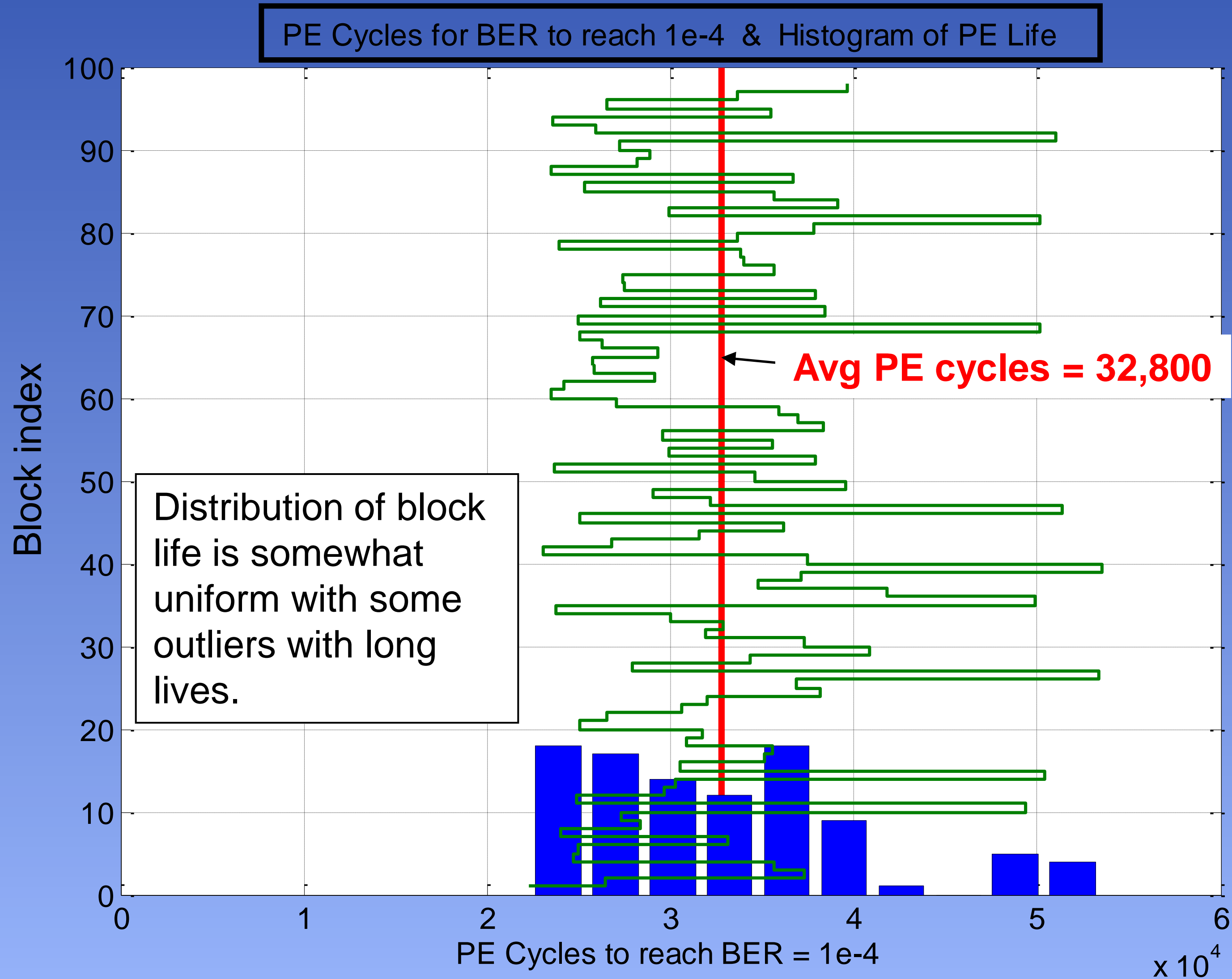


Predicting Block Life

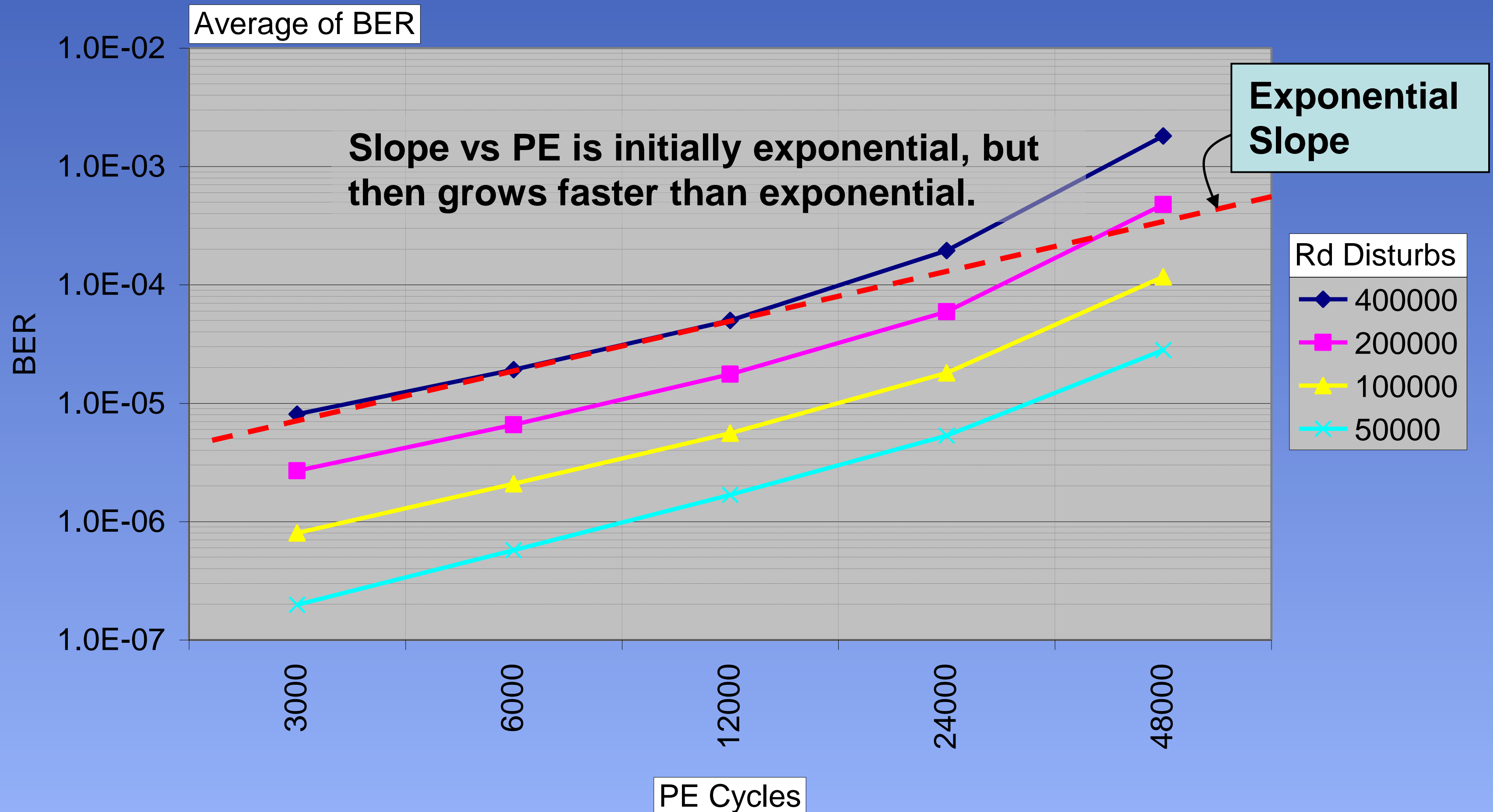
Rank Ordering at EOL vs Rank Ordering at Beginning of Life



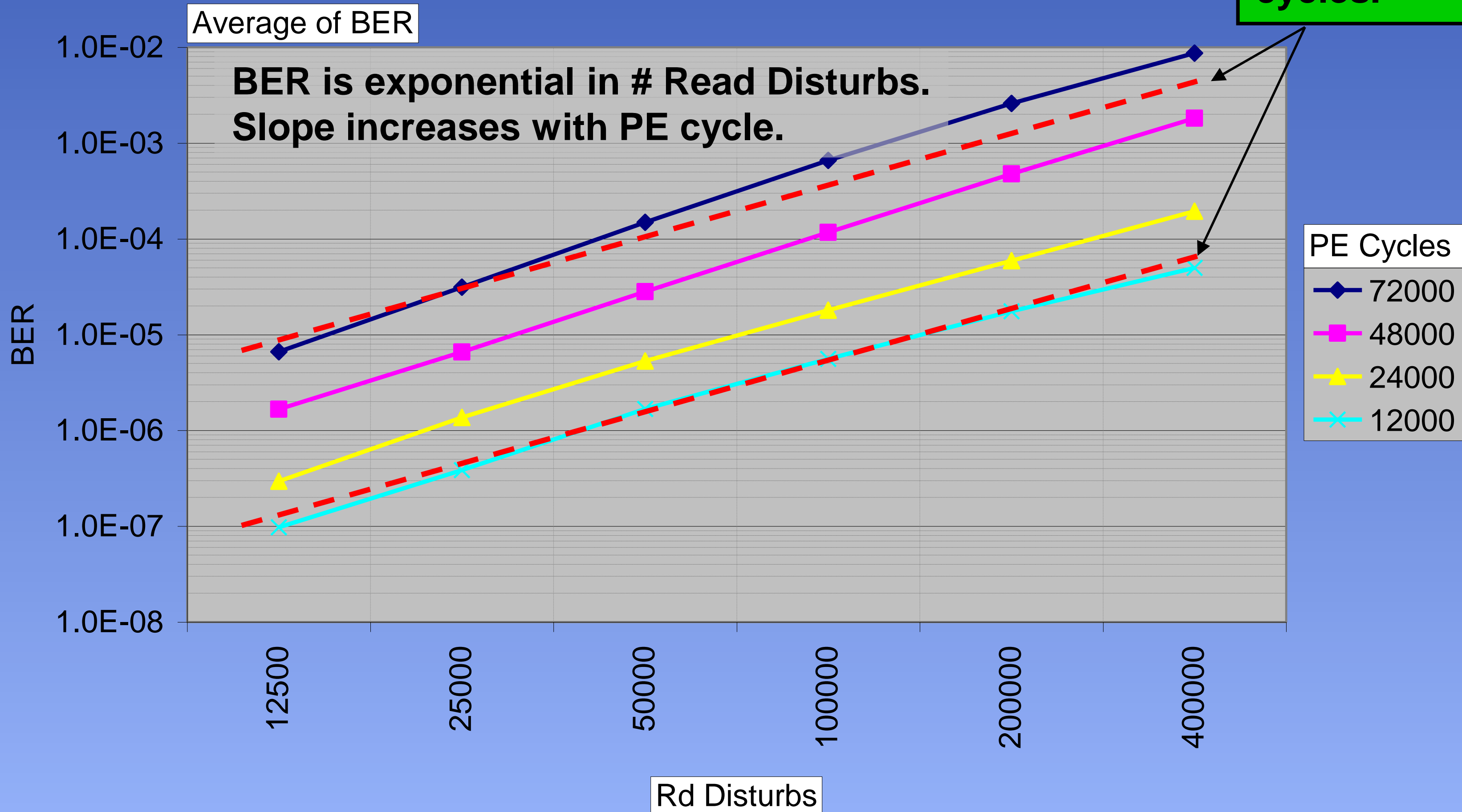
Distribution of Block Life (after 200k Reads)



BER vs PE & Read Disturbs

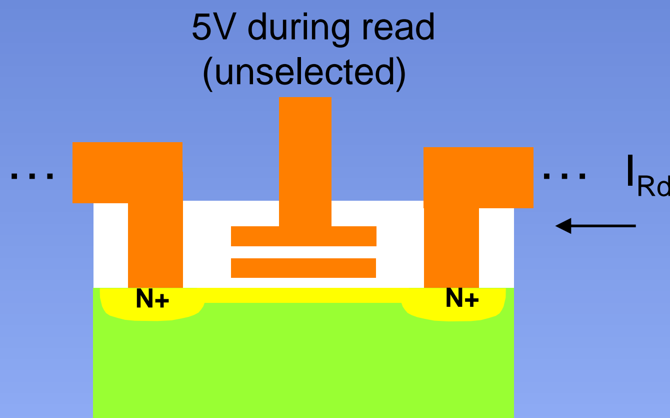


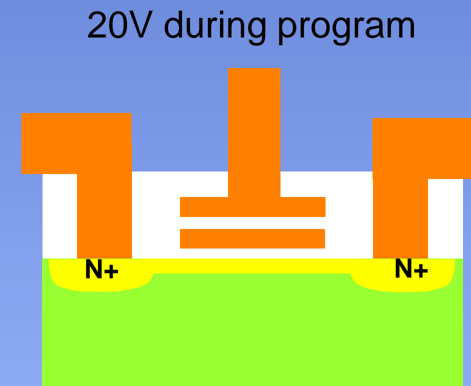
BER vs Read Disturbs & PE Cycles



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.





Flash Memory SUMMIT

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 BER early in life captures trends, but misses many exceptional blocks.
  - Block performance is generally well correlated with adjacent block performance.