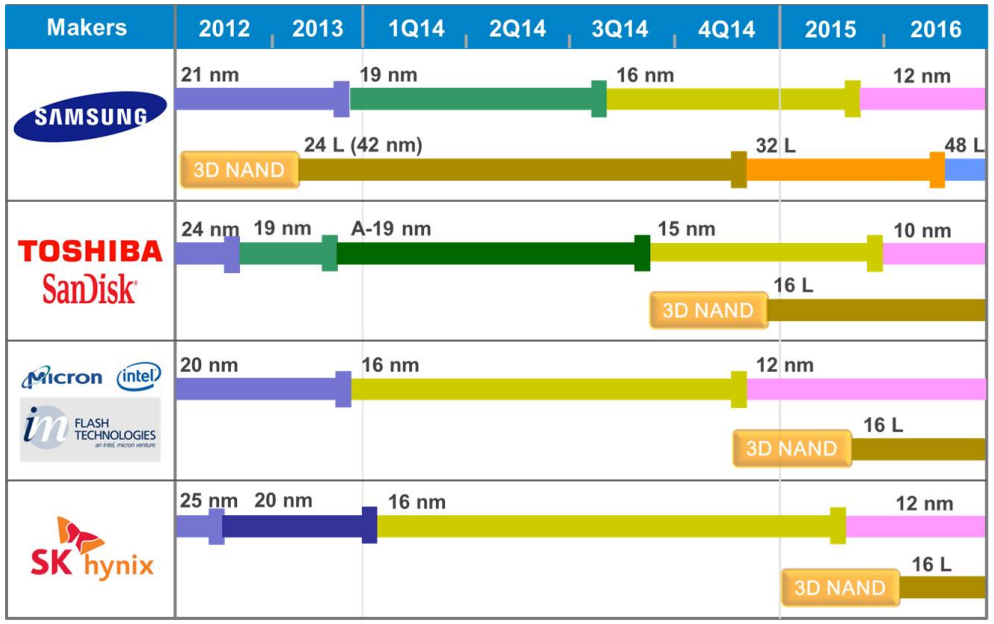
How Much Can Data Compressibility Help to Improve NAND Flash Memory Lifetime?

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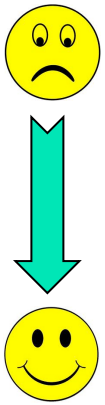
NAND Flash Memory



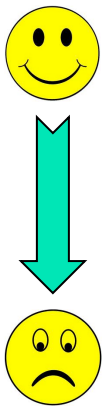


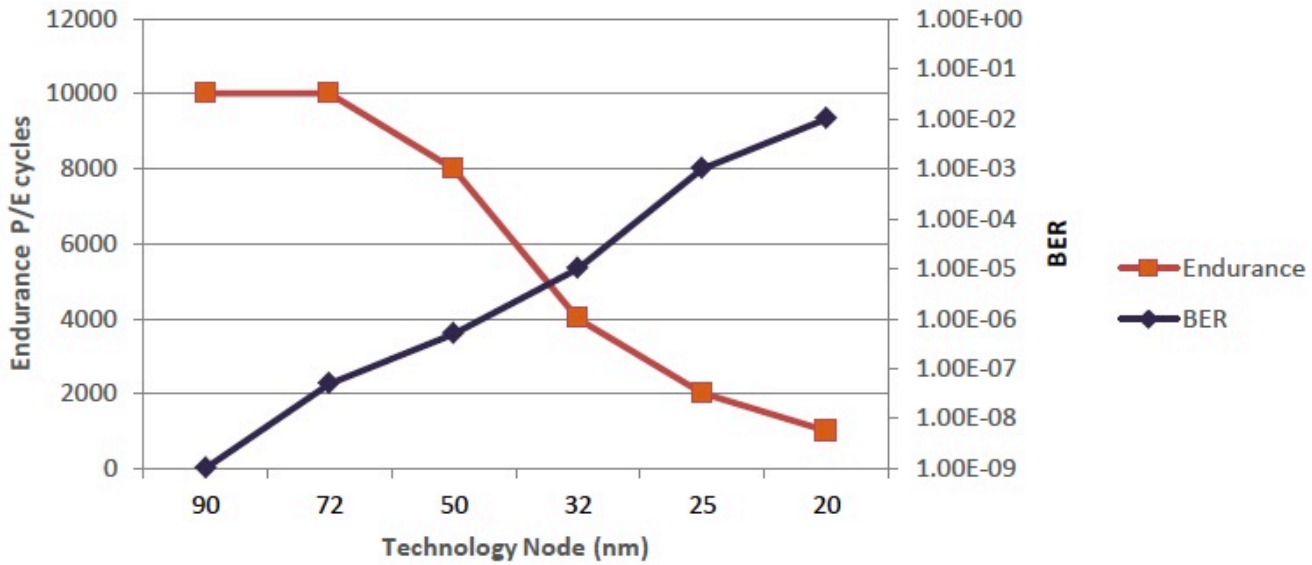
Bit cost reduction

Price/GB



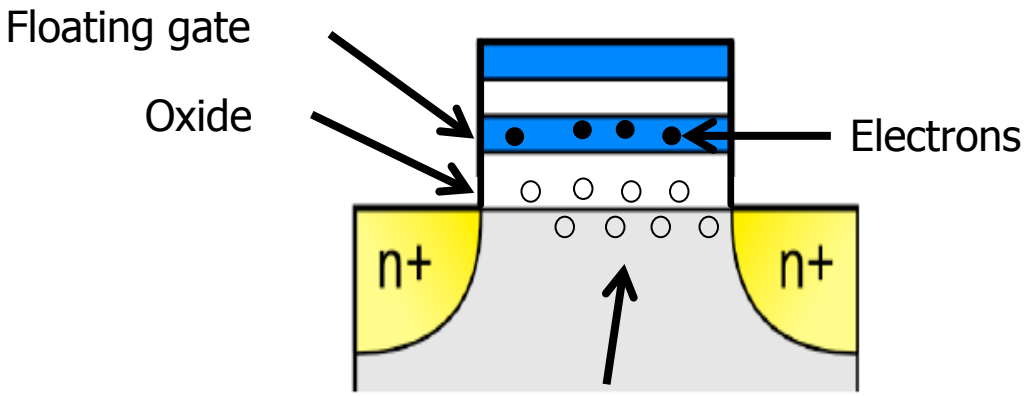
Lifetime





Damage of NAND Flash memory cell

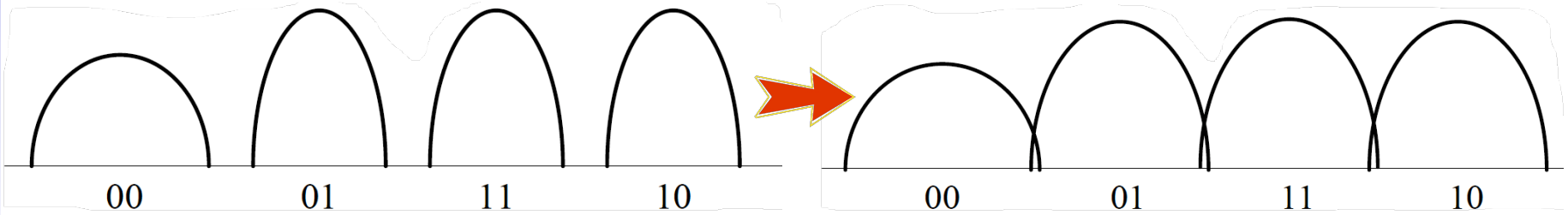
- Damage to the NAND Flash memory cell



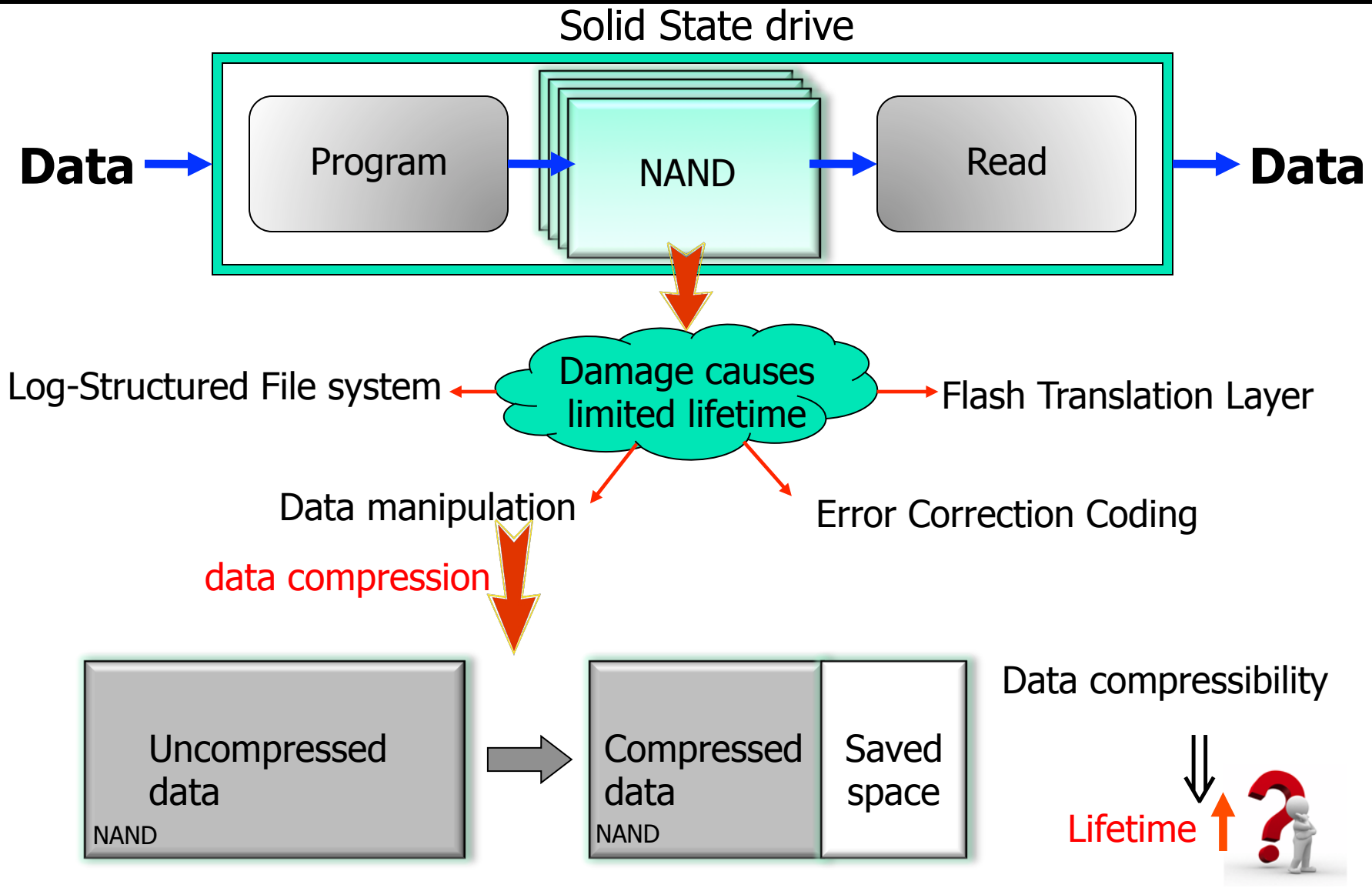
- Oxide layer becomes thinner
- Number of electrons held in floating gate is reduced

P/E cycling causes **Charge trap : Damage** to memory cell

- Threshold voltage distribution overlap



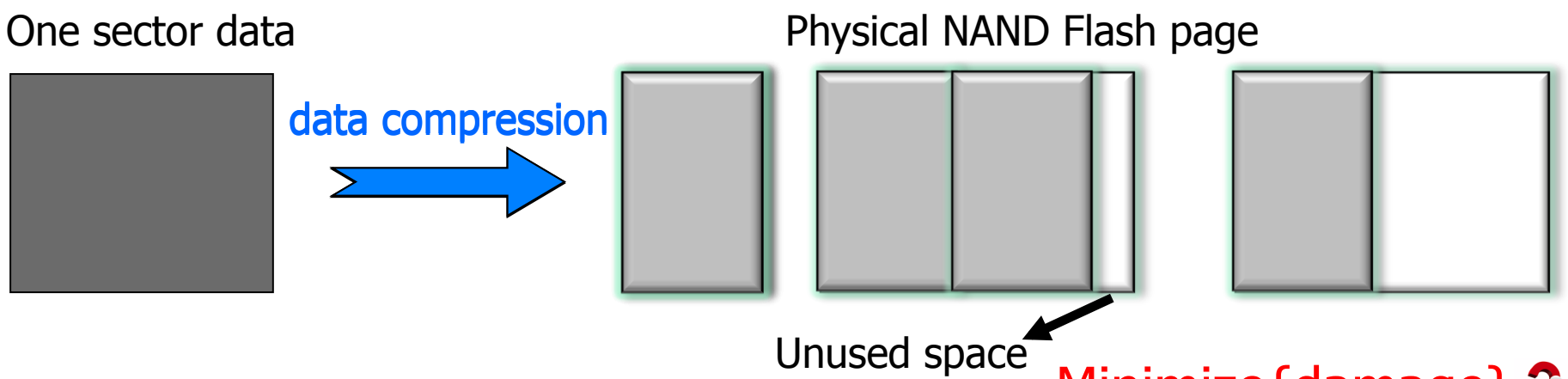
Method to improve the lifetime



Data compression in NAND Flash

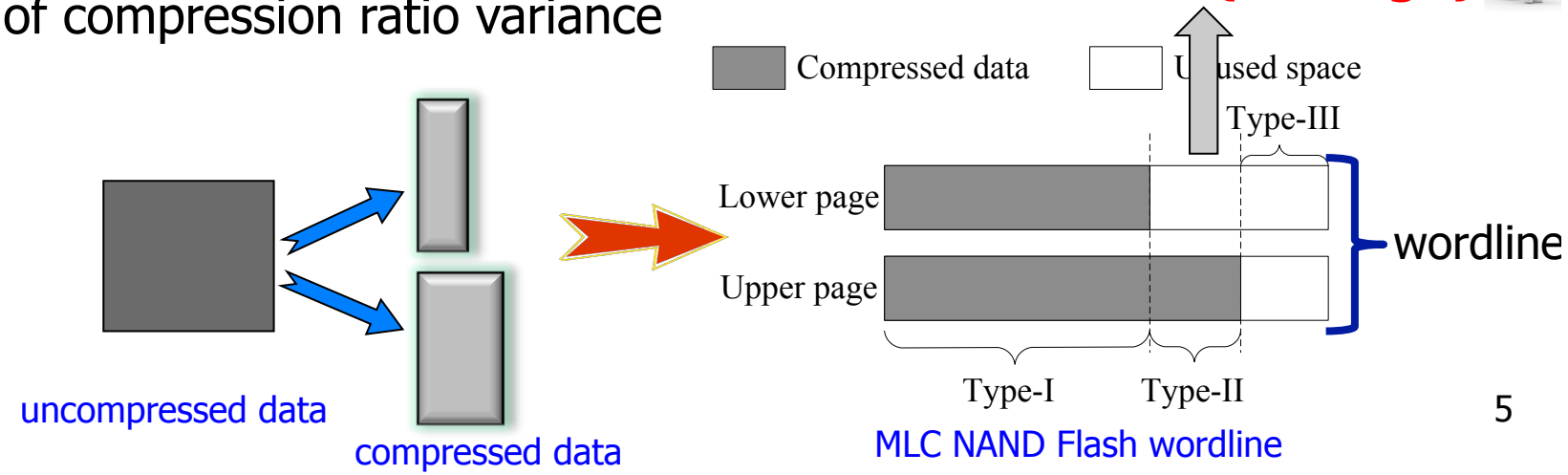
Data compressibility :α ⇒ Lifetime extends: $1/\alpha$

- Unused space in one NAND Flash page

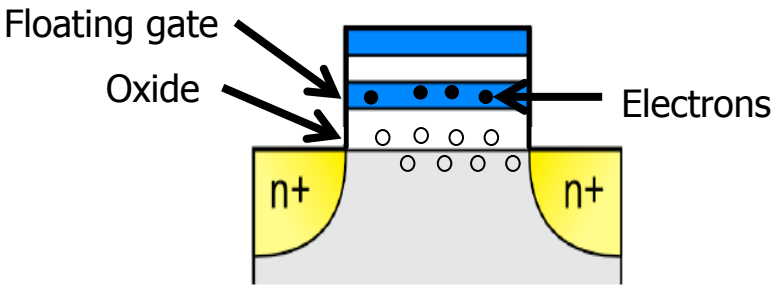


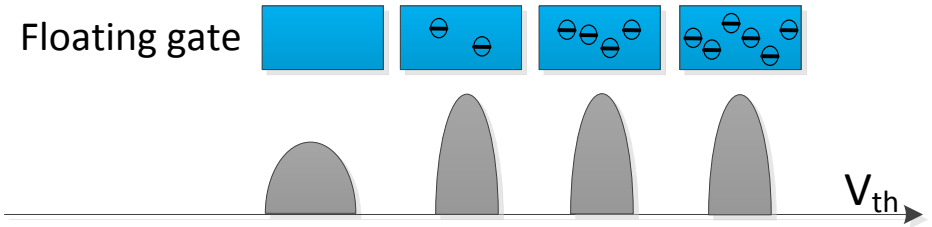
Minimize{damage}

- Impact of compression ratio variance



Content-dependent damage characteristics



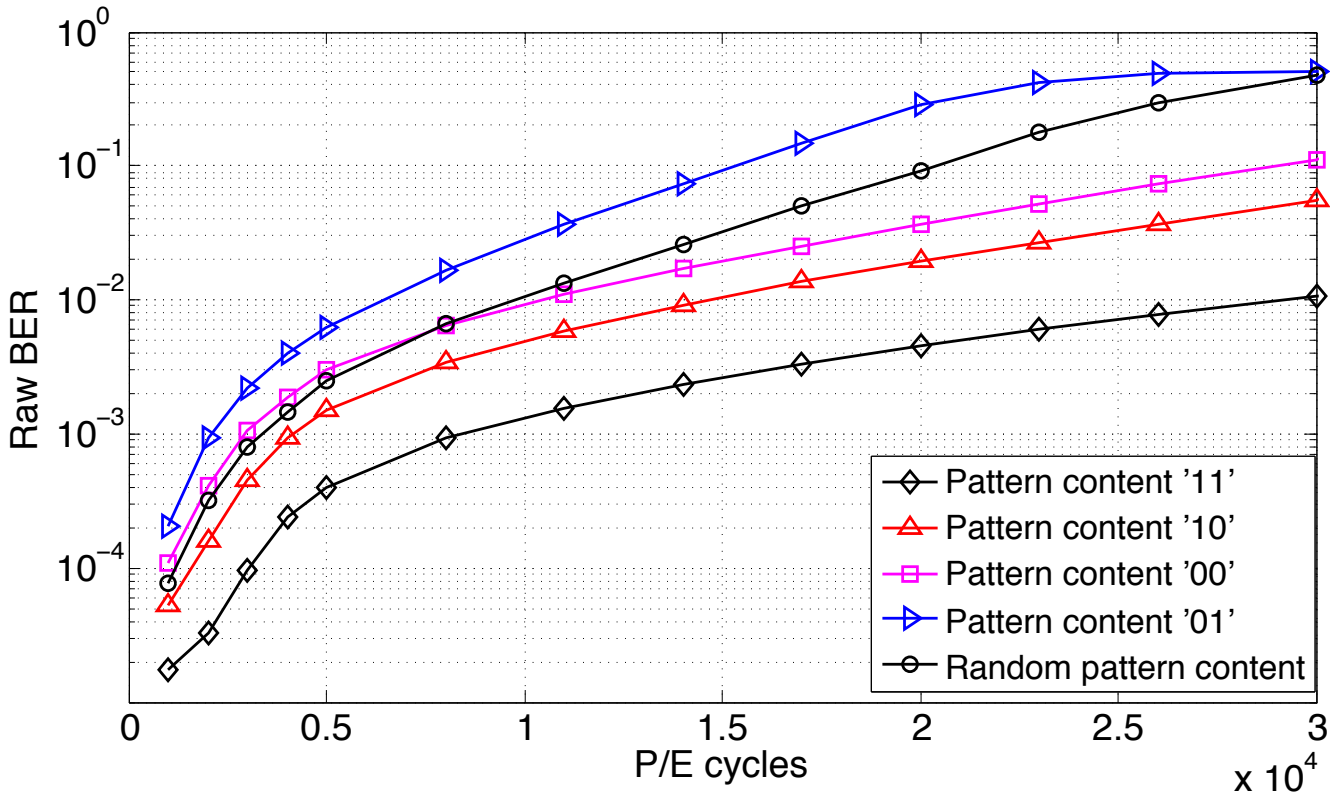


State	'Erase'	'P1'	'P2'	'P3'
Lower page	1	1	0	0
Upper page	1	0	0	1

- Electrons quantity differentiate the damage of data patterns
- **NAND Flash memory experiences content-dependent memory damage**
- Damage of data pattern:

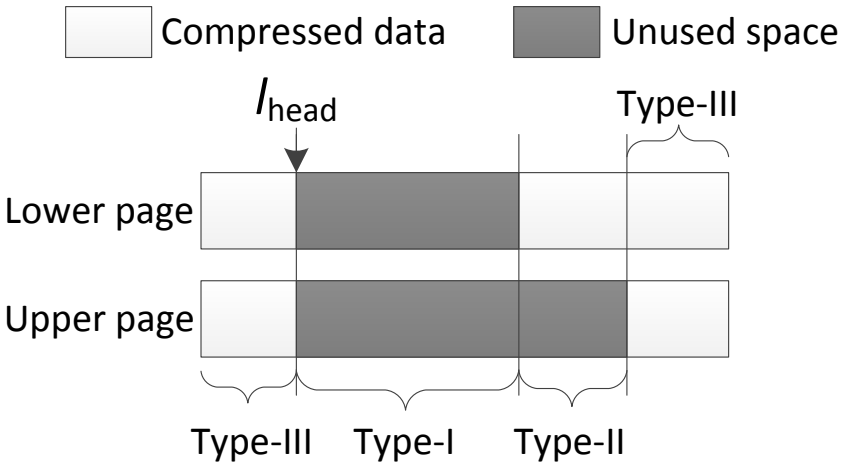
  pattern "11" < pattern "10" < pattern "00" < pattern "01"

Content-dependent damage: test result



20nm MLC
NAND Flash chip

Unused space filling strategies



Increase pattern "11" and "10";
Decrease random data pattern and "01"

Unidirectional data layout (UD)

$S^{(l)}$: Unused space in lower page
$S^{(u)}$: Unused space in upper page

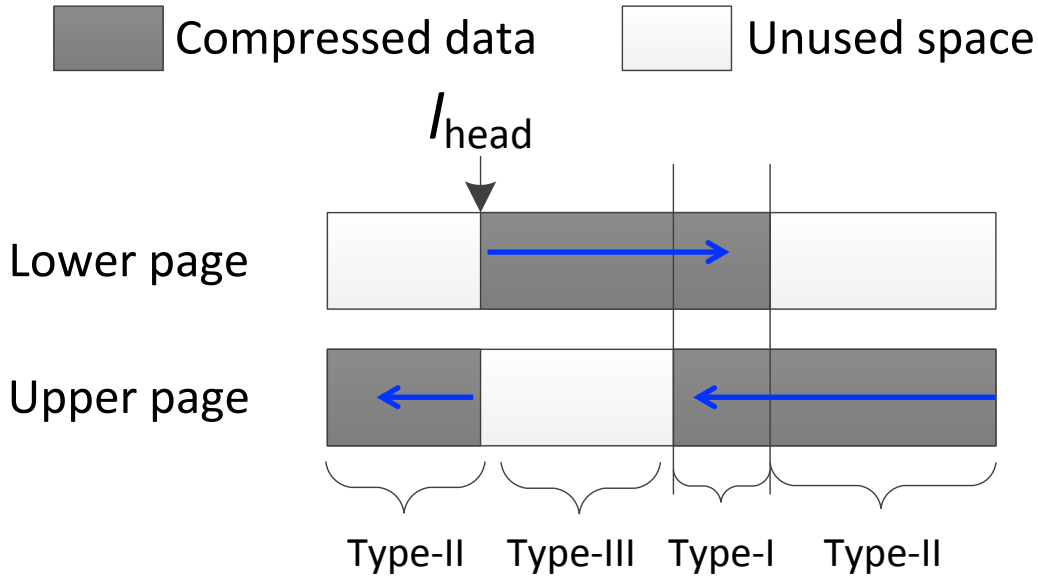
b_l: lower page bit in memory cell k
b_u: upper page bit in memory cell k

Unused space filling rule:

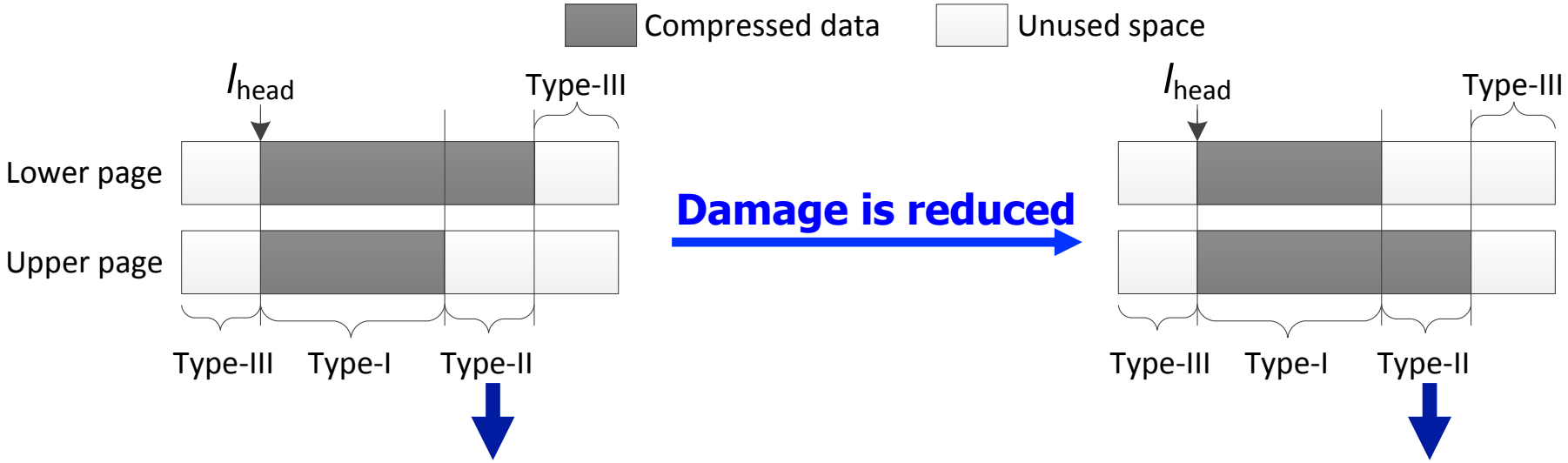
- If $b_l \in S^{(l)}$ and $b_u \in S^{(u)}$ (Type-III)
  Set $b_l = b_u = 1$;
- If $b_l \in S^{(l)}$ and $b_u \notin S^{(u)}$ (Type-II-a)
  Set $b_l = 1$;
- If $b_l \notin S^{(l)}$ and $b_u \in S^{(u)}$ (Type-II-b)
  Set $b_l = b_u$.

Bidirectional data layout

- Bidirectional data layout (BD): To reduce the percentage of random data pattern (Type-I)



Conditional data exchange



Type-II: pattern "11" or "00"

Type-II: pattern "11" or "10"

damage of "10" < damage of "00"

- Conditional data exchange: **exchange the compressed lower page data with upper page data to ensure the compressed lower page data has larger unused space**

May introduce extra overhead for FTL

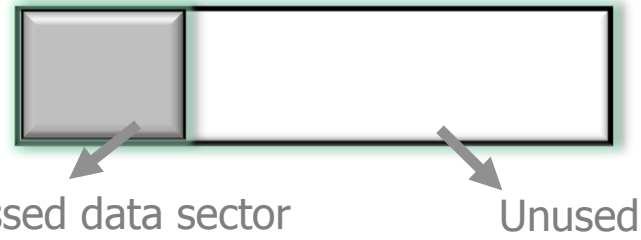
Explicit compression and implicit compression

- Conventional compressed data storage : Explicit compression



  - Complicate FTL/file system design

- Implicit compression : A transparent data compression stored method

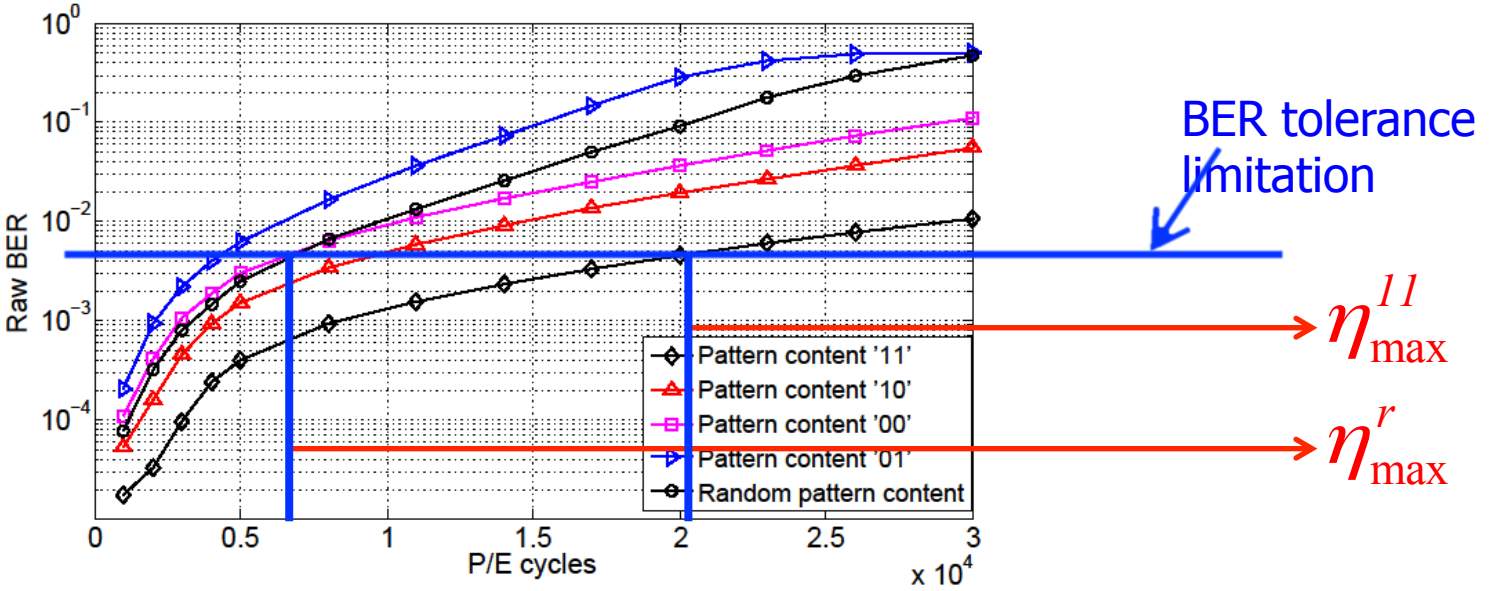


Compared with non-compression storage, the number of data sector in one Flash page is not increased

  - Transparent to FTL and file system, simplify system design
  - Sacrifice data compressibility and damage reduction

Damage factor of data pattern

- 20nm MLC NAND Flash test results



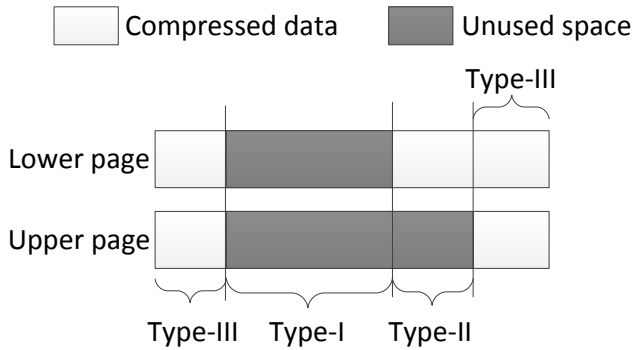
- Damage Factor ρ_i: Measure the damage of data pattern i

$$\rho_i = \frac{\eta_{\max}^{(r)}}{\eta_{\max}^{i}}$$

Mathematical model to evaluate Flash lifetime



Compressed data length in one page: $C_S^{(e)}$



: Model input

: Model output

Data compressibility (mean, variance)

Mathematical model

Distribution of $C_S^{(e)}$

Damage factor of data patterns

Mathematical model

Distribution of memory cell damage per P/E

NAND Flash physical parameters

Mathematical model

Wordline survival probability

Mathematical model

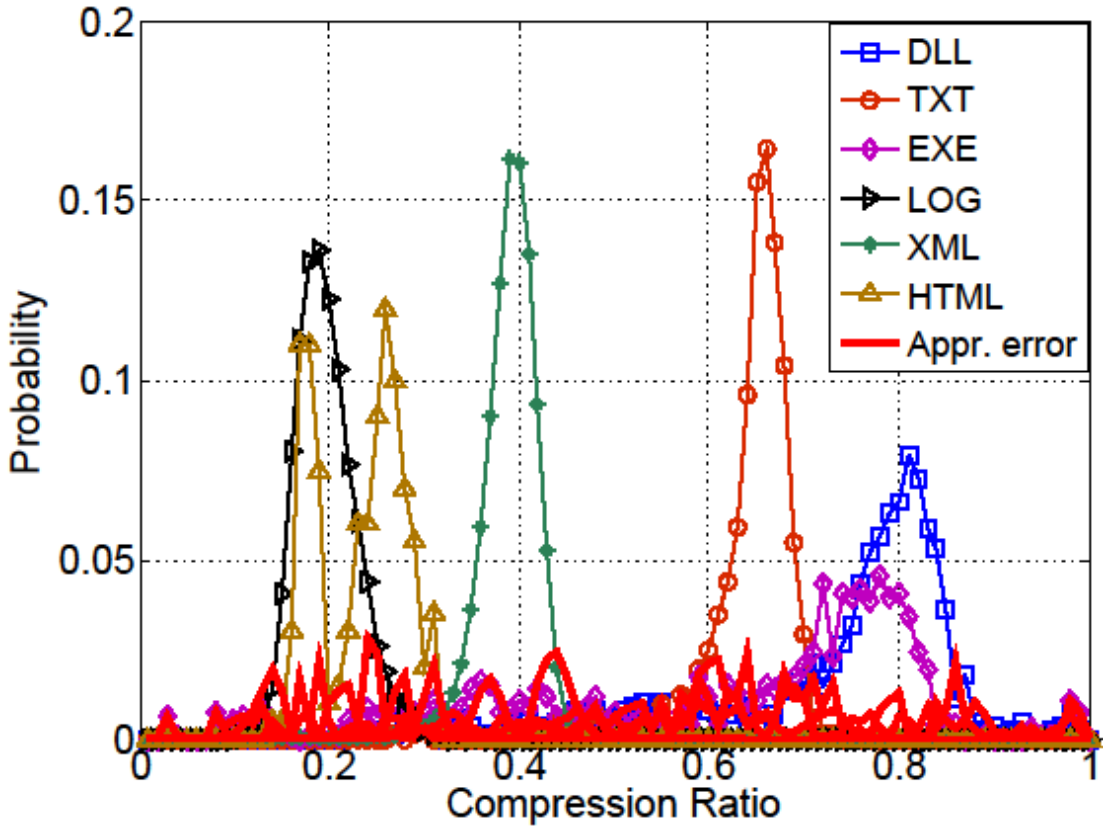
Block survival probability

Mathematical model

After *t* P/E cycles, NAND Flash memory device survival probability

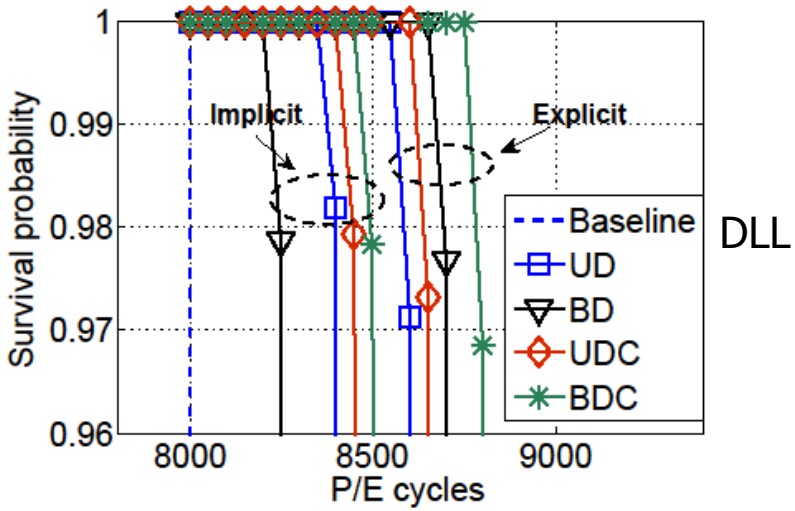
Simulation results

- Selected data compressibility (LZ77 compression algorithm, 4kB data sector length)

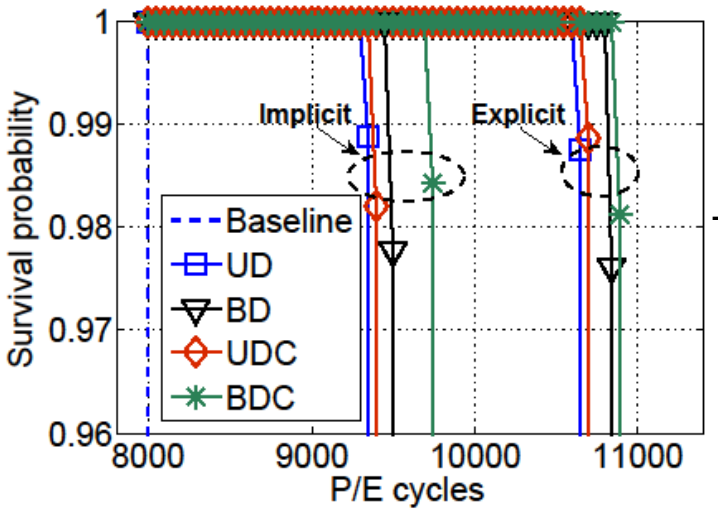


Simulation results

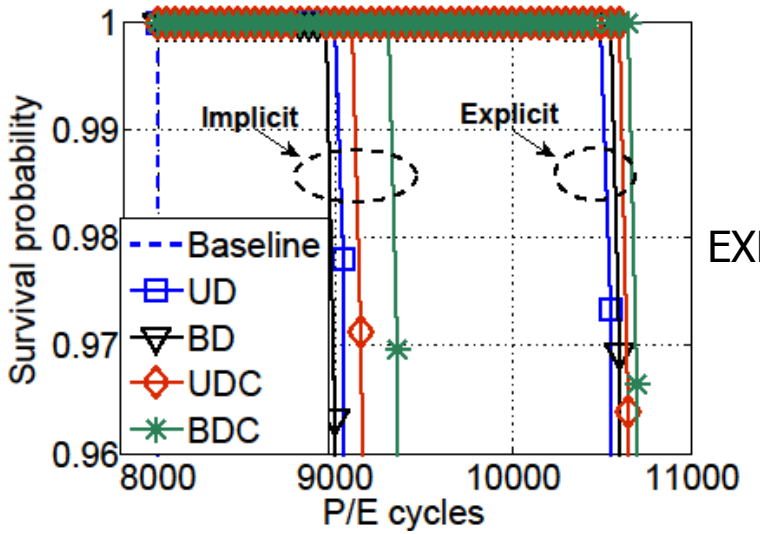
- Lifetime improvement by data compression storage techniques



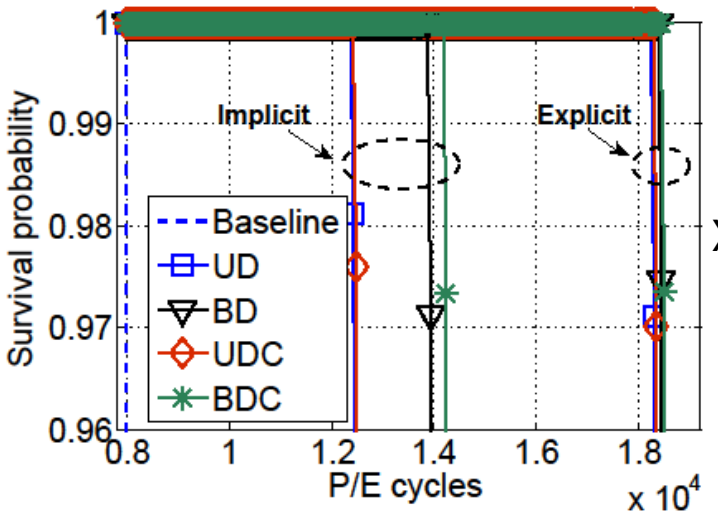
DLL



Text



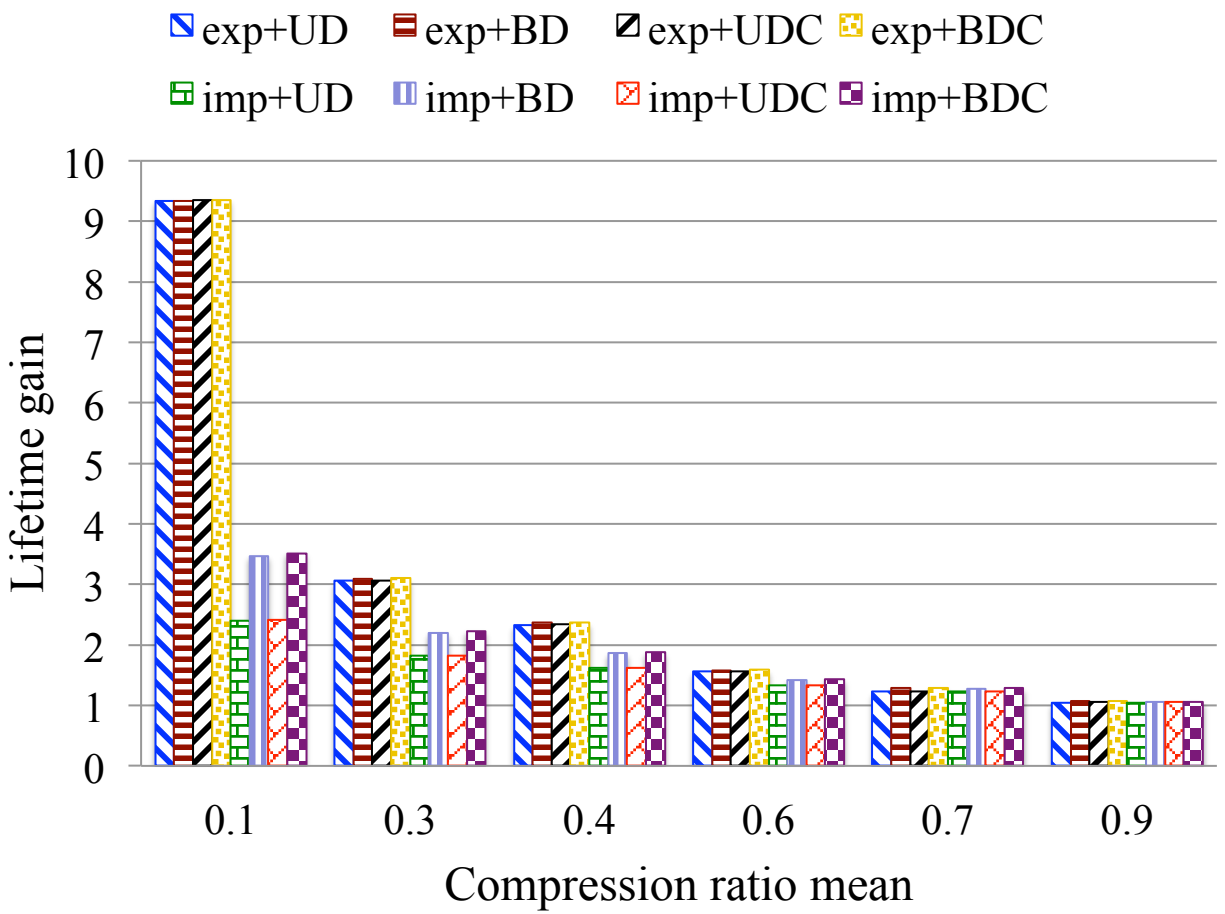
EXE



XML

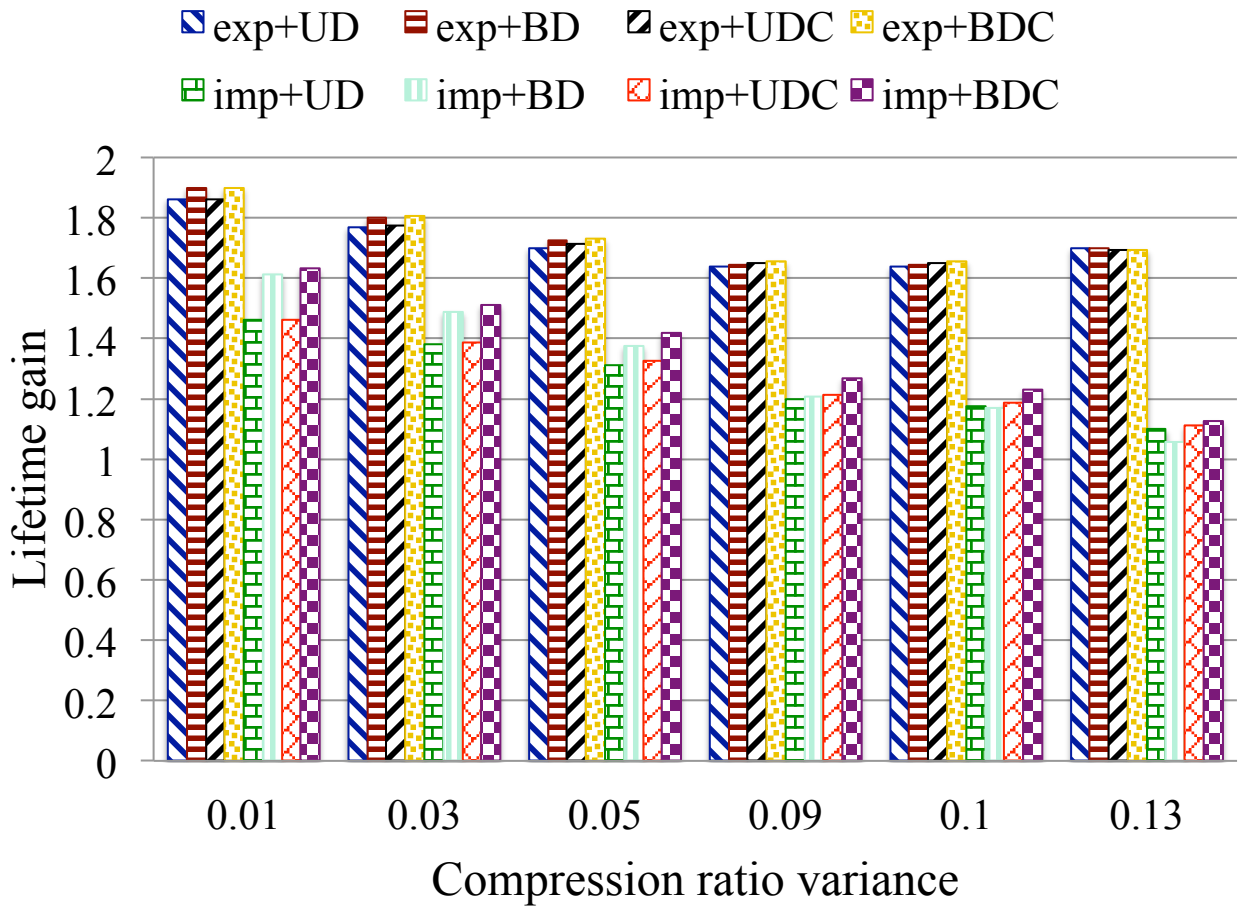
Impact of data compression ratio mean

- Compression ratio standard deviation fixes at 0.01



Impact of data compression deviation

- Compression ratio mean fixes at 0.5



Conclusion

- Research on the employing data compressibility to reduce NAND Flash physical damage, in order to improve memory lifetime
  - Content-dependent damage feature of MLC NAND Flash to reduce damage from data program and erase.
  - A set of design strategies to exploit unused space from data compression in order to minimize the overall memory damage.
  - File system/FTL-friendly implicit compression as a complementary of conventional explicit compression.
  - Mathematical model to evaluate NAND Flash memory lifetime based on the data compressibility.