Mitigating Inter-Cell Coupling Effects in MLC NAND Flash via Constrained Coding

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Problem Definition: Inter-Cell Coupling
Related Work
Novel Solution: Constrained Coding System
An Example
Conclusions
Inter-Cell Coupling

- FG-FG inter-cell coupling causes the charge in one cell to affect a neighboring cell’s threshold voltage.
V_t Distribution Widening

- When considering each cell in isolation, the observed phenomenon is a “widening” of the threshold voltage distributions.

Distribution Widening due to Inter-Cell Coupling
Coupling – a Model

- Neglecting $C_{FGXY}$, and assuming $Q_{FG}=0$ the floating gate voltage due to ICC is:

$$V_{FG} = \frac{C_{ONO} V_{CG} + C_{FGX} (V_1 + V_2) + C_{FGY} (V_3 + V_4) + V_{FGCG} (V_5 + V_6)}{C_{TUN} + C_{ONO} + 2C_{FGX} + 2C_{FGY} + 2C_{FGCG}}$$
**Coupling with Program & Verify**

- **Program & Verify:**
  - Charge is added to a cell in small increments
  - $V_t$ is checked after each addition
  - Programming ceases upon reaching the desired $V_t$

- Therefore, $V_t$ of any given cell is affected only charge changes made to its neighbors after its own charging has been completed.

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The effect of inter-cell coupling depends on the programming scheme.
Existing Coupling-Mitigation Schemes

- Proportional programming
  [Fastow et al, USP 6,996,004]

- Intelligent read decoding
  [Li et al, USP 7,301,839]
Proportional Programming

- Concurrent, incremental programming of all cells, tailored for near-simultaneous completion.

- Pros:
  - Desired $V_t$ for all cells (altered only by the last pulse of each neighbor);
  - Narrow distributions.
  -Insensitive to coupling parameters.
  - Simple read

- Shortcomings:
  - Complicated, possibly slow programming
  - Can’t account for next line if programmed later
  - Can’t fully compensate when “pull” is greater than desired level (would require negative “bias”)

[Fastow et al]
Intelligent Read Decoding [Li et al]

- Simple, conventional programming
- Based on coupling equations, parameters and on programming scheme, decode smartly to offset coupling effects.

**Pros:**
- Simple programming
- Overlapping distributions are separated by decoding

**Cons:**
- Must know coupling parameters; no variation allowed.
- Requires accurate reading of $V_t$
- Complex, slow read
Our Approach: Constrained Coding

- Forbid certain adjacent-cell level combinations:
  - Criterion depends on programming order
  - Threshold is a design trade-off
- Programming: use only permissible combinations (legal code words)
- Decoding: use inverse mapping
Constrained Coding – Main Features

- **Pros:**
  - Limits the effect of inter-cell coupling → narrow distributions → many levels
  - Fairly simply encoding and decoding
  - Only need to know an upper bound on coupling coefficients

- **Cons:**
  - Code rate <1 → some loss of capacity relative to ideal with narrow distributions.
Constrained Coding - Remarks

- Can easily be combined with ECC

- Complementary to the previous schemes and can be combined with them:
  - Semi-accurate programming + minimal restrictions
  - Some restrictions with simpler intelligent read decoding
Constrained Coding System

All combinations available

Decoder recovers original data
Example: 1-D, “Breadth 1st” Coding

- 1-D: a single row of cells is considered
- Programming (charge & verify)
  - All >0 cells programmed to level 1
  - All >1 cells programmed to level 2
  - ...
- Sequence eligibility criterion:

\[
D(C) = \max \{N_L - C, 0\} + \max \{N_R - C, 0\} < T
\]

- T represents a trade-off:
  - Large T: efficient coding, but wider distributions and fewer levels
  - Small T: opposite pros and cons

\(N_L, C, N_R: \text{respective target levels}\)
Required Redundancy ($T=5.2$ bpc)

$$\text{Redu}(S) = 1 - \lim_{l \to \infty} \frac{\log_2 N(l; S)}{l \log_2 n} = 0.0483$$

- Notation:
  - $N(l; S)$ - number of legal (permissible) $l$-symbol code words
  - $n$ - number of program levels in a cell
  - $S$ - language of all legal code words
- The required redundancy is (at least) 4.83%
Capacity Implication (T=5)

- Assumption: constrained coding permitted an increase in the number of levels from 4 to 5.

- Baseline:
  \[1.0 \cdot \log_2 (4) = 2\]

- Constrained coding:
  \[0.95 \cdot \log_2 (5) = 2.2 > 2\]

- A 10% increase in capacity
We build graph of the constraint language

• With 4 levels per cell, this example excludes the combinations (sequences) 3-0-3, 3-0-2 and 2-0-3.
For demonstration, consider code rate $= \frac{2}{3}$

For this, we can build a lookup table and use it.
The design can also be implemented with state machine. E.g., to exclude 3-0-3:

Encoding Input

00/331
01/322
02/332
03/000
10/111
11/222
12/231
13/232
20/233
21/131
22/132
23/133

30/323
31/333
32/223
33/113

Encoding Output

00/000
01/011
02/012
03/022
10/010
22/100
23/333
21/222

30/223
31/323
32/113
33/123
Conclusions

• Constrained coding can be used to chop off the tail of $V_t$ distributions with only a minor reduction in coding rate

• Can be used beneficially to increase capacity or to increase reliability

• Can replace proportional programming and intelligent decoding or complement them

• Detailed papers in preparation

• A patent application has been filed by Technion
End

Questions?

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