Radiation Qualification of Flash Memories

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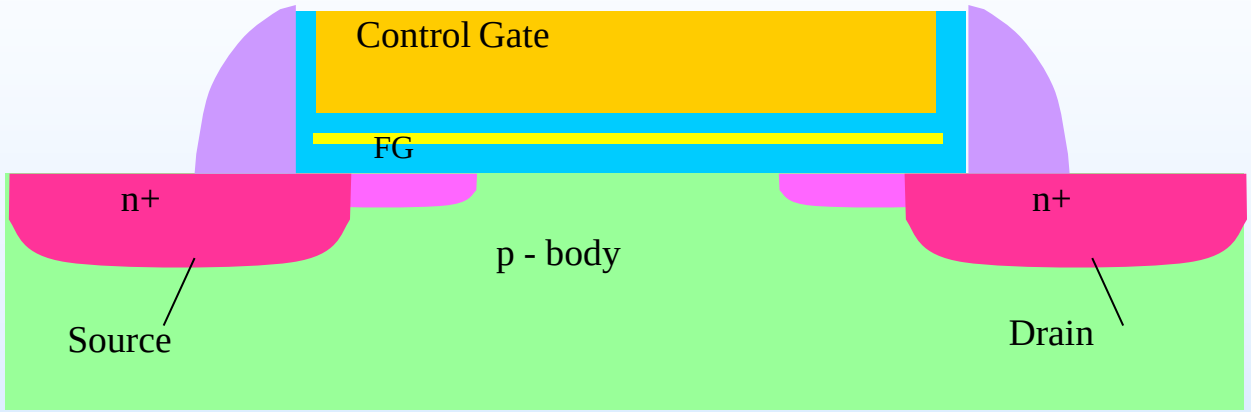
Outline

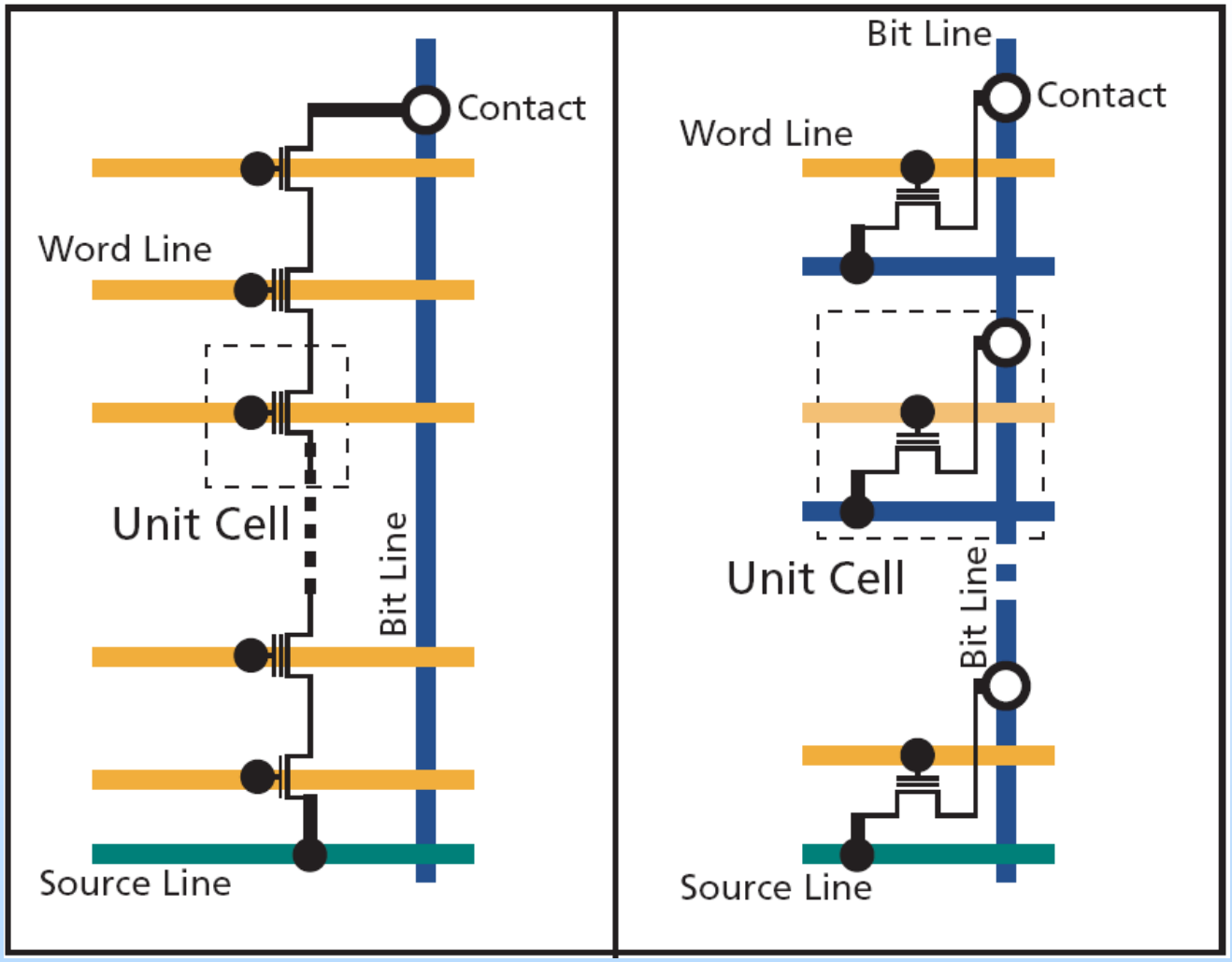
- Introduction/Background
  - Flash Technology
  - Test Modes
  - Error Correction
  - Single Level Cell/Multi-Level Cell
- Total Ionizing Dose (TID)
- Heavy Ion SEE
- Proton Testing
- Combined Effects (Radiation/Reliability)
- Conclusions

Floating Gate Transistor



- **Write (Program) operation—Fowler-Nordheim (FN) injection of electrons into FG**
- **Erase operation—FN injection of electrons from FG to substrate**
- **Repeated P/E operations cause damage to tunnel oxide**
- **High voltage charge pumps are critical to Program and Erase operations, usually the first thing to fail**

Flash Architectures



NAND NOR

Flash Advantages

- **Low cost per bit**
- **Low Power**
- **Nonvolatile**
- **Attractive for space applications for the same reasons widely used in hand held, battery powered, consumer electronics**
- **Radiation response is variable, as one would expect for unhardened commercial technology, but often pretty good**

Operating/Test Modes

- **Typically have dozens of test modes, can only test a few**
- **Static mode, unbiased**
- **Static mode, biased**
- **Dynamic Read**
- **Dynamic Read/Write**
- **Dynamic Read/Erase/Write**
- **New! ONFI (Open NAND Flash Interface) enables high throughput (133 Mbytes/sec)**

Error Correction

- **Most NAND flash does NOT meet its performance or reliability specs without ECC**
- **Since ECC is critical to the system, it should be part of the test**
- **Most SLC NAND has about 3% redundant memory for ECC; e. g. 8G NAND has pages 4Kx8, or 32 Kbits, with an additional 128 bytes (1024 bits) for ECC**
- **Simple Hamming code for a memory segment of 2^N bits requires N+1 bits for SEC (single error correction), or N+2 bits for SEC-DED (SEC-double error detection)**
- **Redundant memory is sufficient to hold SEC or SEC-DED Hamming code to correct one bit of every 512 bits**

SLC/MLC

- **Single Level Cell NAND is typically specified as having 10^5 P/E cycle endurance, and 10 year retention**
- **Multi-Level Cell NAND typically has 5000 P/E cycle endurance with 10 year retention**
- **MLC requires more robust error correction, because initial voltage margins are smaller**
- **New products being introduced by the industry are overwhelmingly MLC**

TID Testing

- In accordance with MIL-STD-TM 1019.8, using Co-60 γ-source, nominal V_{DD} + 10%, at room temperature
- DOD Test Guideline document recommends five parts, minimum—we prefer five in Read Only mode and five more fully exercised at each dose level
- TID response of unhardened commercial NAND flash memories varies widely among manufacturers and among technology nodes for a given manufacturer, but the best results are very good
- NAND flash sometimes survives TID exposure past 100 krad (SiO_2)—good enough for most NASA missions
- NOR flash is much more sensitive than NAND flash

Heavy Ion SEE Testing

- In accordance with ASTM F1192
- Try to get data with at least four ions (different LETs), and check for angular effects
- Use all test modes: Static, with and without bias; Dynamic Read; Dynamic R/W; Dynamic R/E/W
- Control logic errors (SEFIs) more important than single bit upsets
- Functional failures usually associated with high voltage Write and Erase operations, usually due to charge pump failures

Control Logic Errors

ERRCnt	DATA	EXP	BIE	BLOCK	PAGE	COL	
1	2	0	1	2509	13	907	1
2	2	0	1	2509	13	925	
3	32	0	1	2538	37	1245	
4	1	0	1	2540	58	1328	
5	16	0	1	2541	8	779	
6	32	0	1	2542	39	1208	
7	128	0	1	2543	36	1234	2
8	128	0	1	2543	36	1252	
9	2	0	1	2577	47	952	
10	16	0	1	2586	20	718	
11	32	0	1	2587	57	1783	3
12	32	0	1	2587	57	1801	
13	32	0	1	2602	0	1155	
17	4	0	1	2658	24	1773	
18	4	0	1	2674	26	1767	
19	64	0	1	2697	45	318	
20	16	0	1	2711	20	1386	4
21	16	0	1	2711	20	1404	
22	32	0	1	2714	29	1226	
23	32	0	1	2714	29	1244	
24	8	0	1	2728	33	771	5
25	8	0	1	2728	33	789	

ERRCnt	DATA	EXP	BIE	BLOCK	PAGE	COL	
110	186	170	1	107	20	860	
111	171	170	1	110	31	785	
112	171	170	1	116	63	1603	6
113	171	170	1	116	63	1619	
114	171	170	1	116	63	1621	
115	171	170	1	116	63	1639	
116	171	170	1	116	63	1657	
117	171	170	1	124	26	586	
118	171	170	1	124	35	454	
128	171	170	1	206	15	904	
129	234	170	1	218	57	435	
130	234	170	1	234	55	1160	7
131	234	170	1	234	55	1162	
132	234	170	1	234	55	1178	
133	234	170	1	234	55	1180	
134	234	170	1	234	55	1196	
135	234	170	1	234	55	1198	

- **Groups of two or more closely spaced errors, where each word has the same bit in error—ECC would see these as uncorrectable errors**
- **Transient noise in the Read circuit is causing erroneous Reads—these addresses will be correct the next time they are Read**

SEE Lessons Learned

- **Want to keep exposure low enough to avoid collective (multiple ion) effects, but high enough for good statistics—trade offs to make effective use of beam time**
- **Important to estimate event rates in space: flux at LET>60 is less than one ion/cm^2 per 100 years, flux in an accelerator can be 15 orders of magnitude higher**
- **High current events are sometimes caused by multiple ion interactions—not necessarily SEE**
- **Flash memories have bit error rates many orders of magnitude better than standard volatile memories, because of nonvolatile feature**

SEE Lessons Learned (2)

- **Acceptable SEFI rates and functional failure rates depend on the particular system**
- **Mitigation strategies are also unique to the system**
- **Frequently, the SEFI rate and failure rate in space is low enough that the program decides to accept the risk**

Proton Testing

- **Guideline is to do proton test if threshold LET for SEE is <15 MeV/mg/cm^2, which is true for all unhardened commercial flash**
- **The one proton test done on unhardened commercial flash produced no single ion effects, only TID damage**
- **Need for proton testing is unclear**

Radiation/Reliability Combined Effects

- **Endurance and retention after radiation exposure has been tested, and retention failures have been observed**
- **The number of retention errors is small enough that existing ECC can easily correct them, in SLC memories**
- **MLC memories may be more sensitive**
- **So far, no combined effects test is necessary for part qualification**

Conclusions

- **Flash memory offers performance advantages over some other technologies**
- **Unhardened commercial technology has variable radiation response, and always requires testing**
- **Best results obtained in testing commercial flash are very good—it is possible to use them in space**
- **More and more, flight programs are seriously considering flash memory for some applications**