COBHAM

Qualification and Reliability of MRAM Toggle Memory Designed for Space Applications

Matt Von Thun

Cobham Semiconductor and Space Solutions

MRQW

6 February 2020

Engineering Humanity's Reach into Extreme Environments

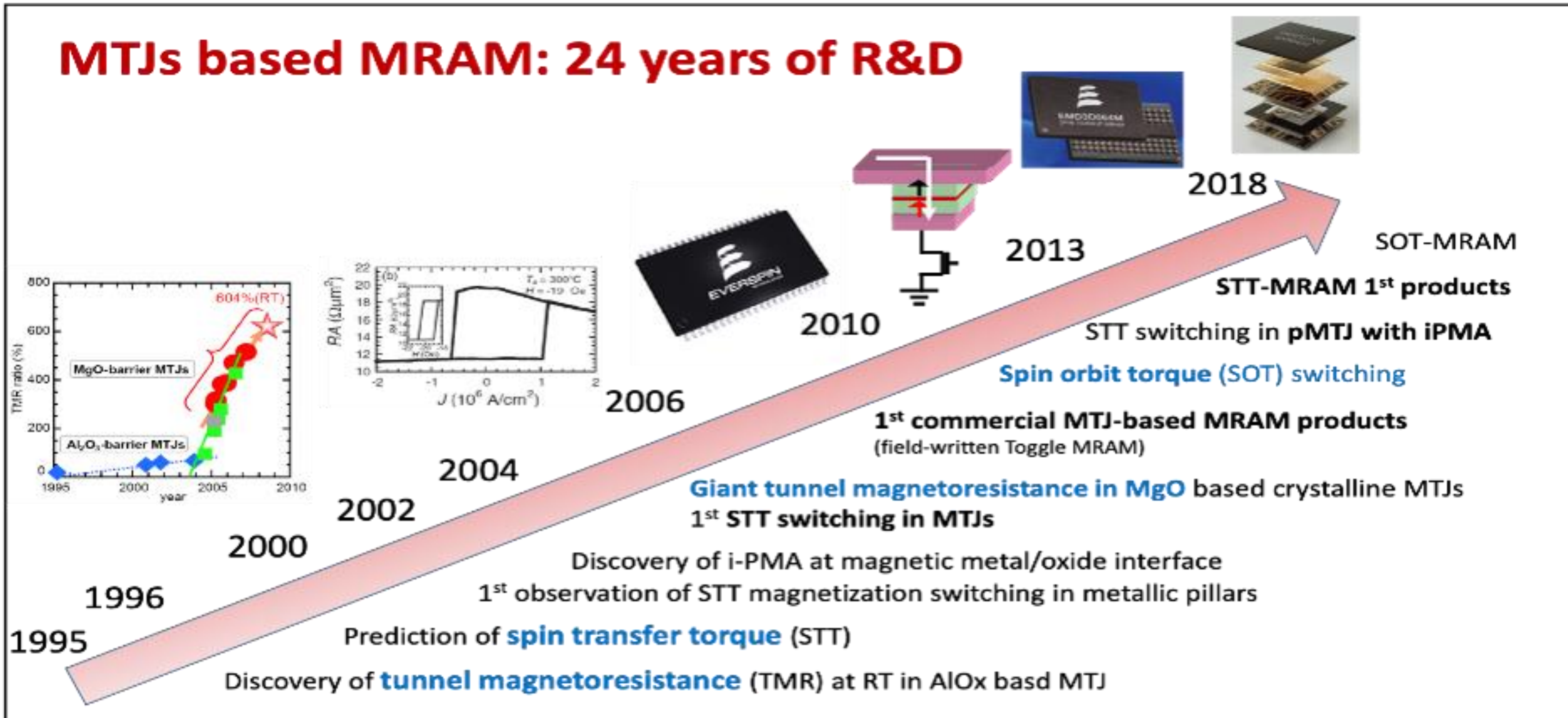
Outline

- Introduction
- Why MRAM for Space Applications
- MRAM Technology
- Development of an Emerging Technology
- MRAM Reliability Evaluation
- Status of Cobham MRAM
- Continuous Improvement for Reliability

Introduction

Emergence of MRAM Technology

- MRAM R&D has been ongoing for 25 years
- Commercial MRAM (Everspin) was introduced 14 years ago
- Space Qualified MRAM (Cobham) is now in its 6th year



Graphical History of MTJ MRAM (B. Dieny)

Why MRAM for Space

Technology Evaluation and Selection

Traditional non-volatile technologies could not meet requested radiation targets

- Circa 2010 … Repeated calls from the Space Community for a TID, SEL, SEGR and upset immune non-volatile memory for critical boot applications
- … pushed industry toward emerging technologies
- MRAM Strengths
  - Bit Cell SEU Immune to >100 $MeV \cdot cm^2/mg$
  - Bit Cell TID Immune to >1 Mrad(Si)
  - Low Voltage (SEGR, SEB immune)
  - Unlimited Endurance
  - Retention beyond mission lifetimes
  - High speed
  - Symmetric Read & Writes

Commercial NVM Technology Survey

Characteristic	Flash	nvSRAM	SONOS	FRAM	CRAM	MRAM
Endurance	10^5	10^6	10^5	10^{10}	$>10^{12}$	$>10^{12}$
Retention (yrs)	>10	>10	>10	>10	< 1	>10
Destructive Read	No	No	No	Yes	No	No
Read Time	90ns	20ns	20ns	100ns	500ns	35ns
Erase/Write Time	10ms	20ns	10ms	100ns	70ns	35ns
High Voltage	Yes	Yes	Yes	No	No	No
SEL	Yes	Yes	Yes	No	Yes	Yes
SEGR Sensitivity	Yes	Yes	Yes	No	No	No
SEU Bit Cell	Yes	Yes	Yes	No	No	No
SHE/RILC Bit Cell	Yes	Yes	Yes	No	No	No
SEFI (data lost)	Yes	Yes	Yes	Yes	No	No
TID rad(Si)	<50k	<50k	100k	>200k	>200k	<100k
Maturity	Good	Moderate	Moderate	Moderate	Poor	Moderate

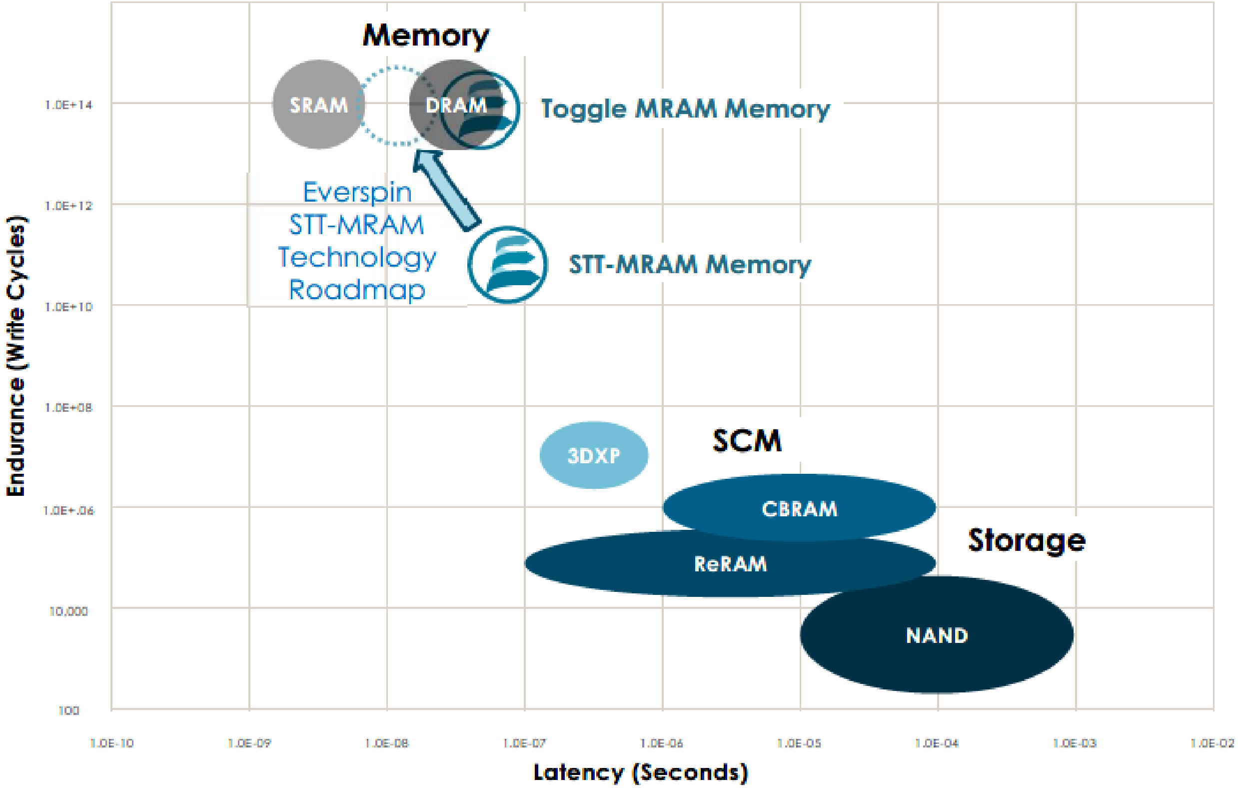
Weaknesses in commercial MRAM fixable by RHBD techniques

Weaknesses in other commercial technologies were intrinsic

MRAM Introduction

MRAM Positioning and Value Proposition

Magnetoresistive **R**andom-**A**ccess **M**emory (MRAM) is a type of non-volatile random-access memory which stores data in magnetic domains



Courtesy of Everspin Inc.

MRAM COMBINES PERFORMANCE OF MEMORY WITH PERSISTENCE OF STORAGE

- **Non-Volatile:** Months to decades of data retention without power or refresh
- **Fast:** Read/write similar to SRAM & DRAM
- **Endurance:** Handles memory workloads

Electron Spin is the Basis of MRAM

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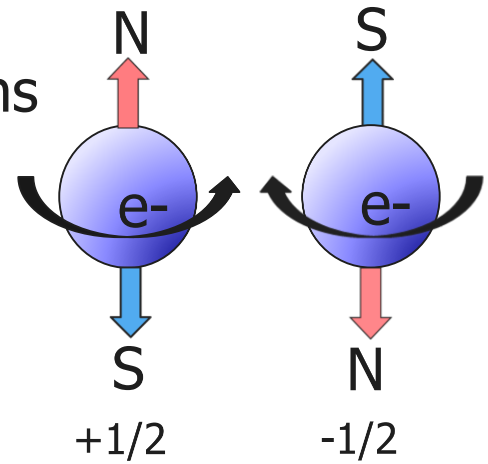
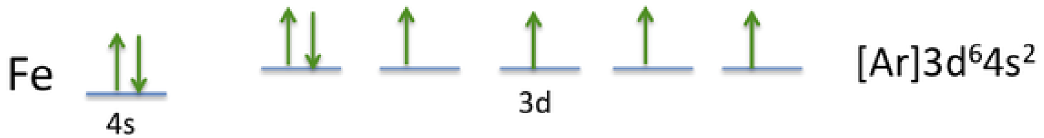
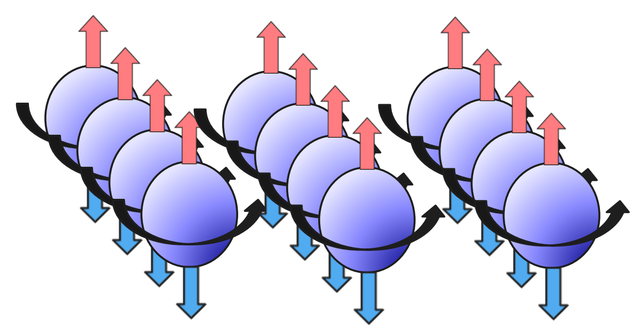
A non-volatile memory not based on charge storage

- Spin is a fundamental quantum number
- Ferromagnetic materials contain unpaired electrons
- Alignment of spin results in magnetism
- Memory is stored in the spin of the electrons
- Spin does not "leak" like charge
- Spin is not affected by heavy ion irradiation
- Spin is not affected by accumulated dose (TID)
- Spin alignment achieved by magnetic fields
- Avoids wear out mechanisms of charge based devices



Spin Quantum Number

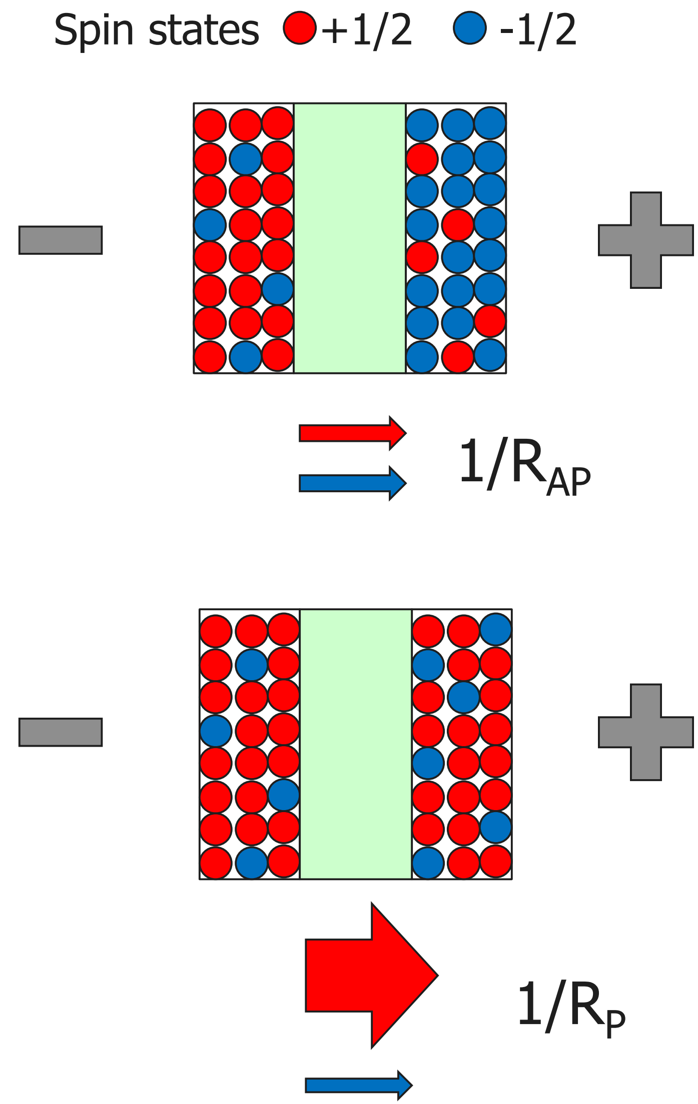




Magneto-Tunnel Junctions

Reading an MRAM Bit

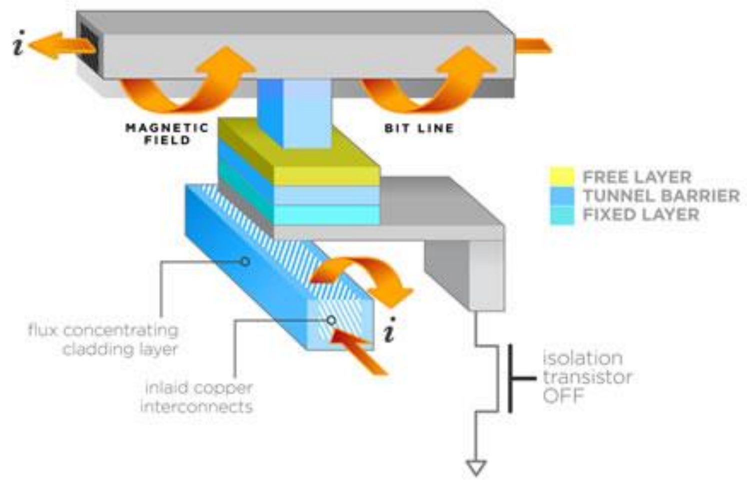
- MTJ = Magneto Tunnel Junction
- TMR = Tunnel Magnetoresistance (Ratio)
- $TMR = \frac{R_{AP} - R_P}{R_P} = \frac{2P_1P_2}{1 - P_1P_2}$
- Ferromagnetic materials have an imbalance of spin up (e↑) and spin down (e↓) electrons
- Electron spin conserved during tunneling
- The total electron current for in a given state is constrained by the minimum number of available states on both sides of the barrier
- Therefore the total current is greater when the magnetic materials on both sides of the barrier are aligned



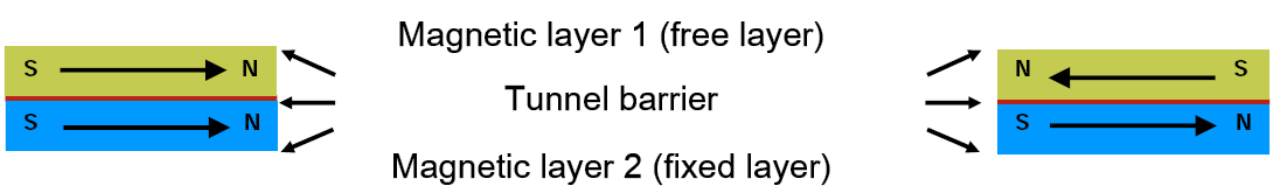
MRAM Bit Cell

Writing an MRAM Bit

- MRAM cell created from a Magnetic Tunnel Junction (MTJ)
- Information stored as magnetic polarization
- Data (polarization) is written by creating a magnetic field with two perpendicular metal lines
- Infinite endurance
- Fast access NVM (35ns to 50ns)
- Non Destructive Read



B. N. Engel *et al*, *IEEE Transactions on Magnetics*, vol. 41, no. 1, pp. 132-136, Jan. 2005



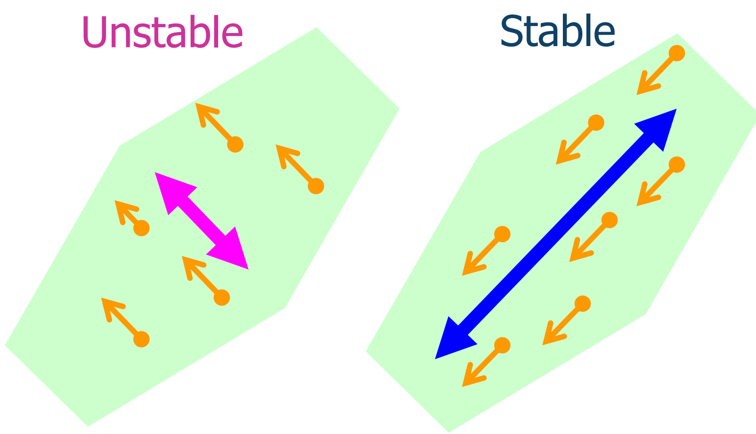
Magnetic vectors are parallel (Low Resistance "0")

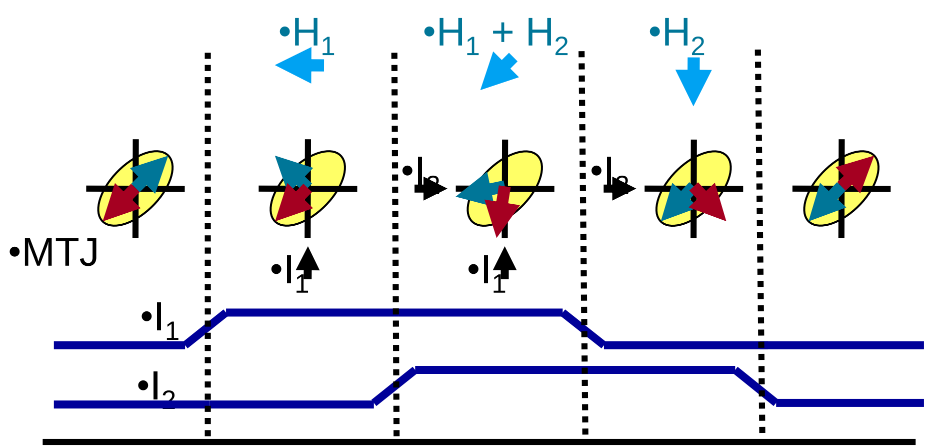
Magnetic vectors are anti-parallel (High Resistance "1")

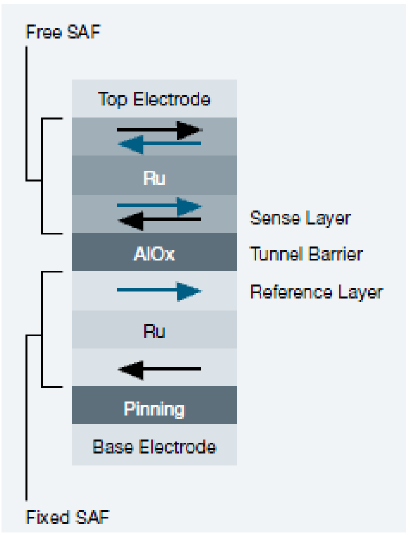
Toggle MRAM Operation

Same flow toggles bit from 1→0 or 0→1

- Long axis displays higher magnetic moment thus becomes “favored” orientation
- In actual device, MTJ is composed of a complex multi-layered Synthetic Anti-Ferromagnetic (SAF) structure
- Ferromagnetic layers resist alignment as would two permanent magnets
- Polarization within SAF layers is modulated by the combined magnetic field vectors H_1 and H_2
- Angled bit cell orientation allows the same pulse sequence to change a 1 to 0 or 0 to 1
- Three step toggle sequence mitigates disturbs







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Developing an Emerging Technology

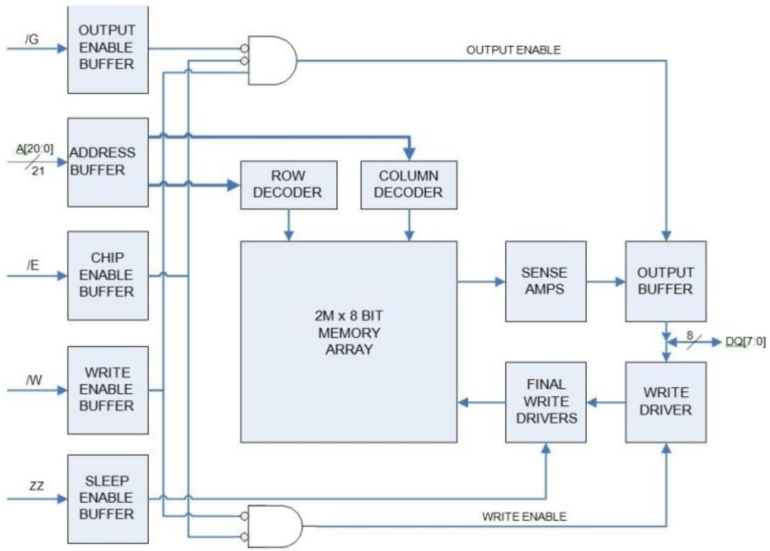
Creating a Strategy to Address Product Development Challenges

- Ken LaBel (NEPP 2010) … Word of warning:
  - *There are ALWAYS more challenges in "qualifying" a new technology device than expected*

Technology Selection	• Remain objective • Fall in love with the problem not the solution	• 13 Technologies Evaluated • Existing, Emerging & Exotic • Sampled and Tested
Technology Evaluation	• Do existing techniques apply • Can commercial data be leveraged • Does target environment effect mechanisms • What must be re-validated	• Expert Partners (Everspin) • Used all available data • Extended Reliability Demo
Define Mission Success	• Performance requirements vs. wish list • Reliability requirements vs. ideals • Screens/Specs - value vs. false security • Quantify Risks	• Government Input (AFRL,..) • Industry Input (Customers) • Re-evaluate as Tech Matures
Design, Fab, Test and Qual	• DFT (Techniques to evaluate mechanisms) • Design for Reliability (including Radiation) • Refine rationale behind specification limits • Refinement of process, screens, flows	• Mil Standard QML-V flow • Monitor beyond Data Sheet • Accelerated Life Test

16Mb & 64Mb RadHard MRAM

Product Details



Block Diagram of 16Mb MRAM

- **RHBD to achieve SEL immunity**
- **RHBD and Process to >1Mrad(Si) TID**
- **Bit cell immune to upset**
- **ECC protects against single bit SER**

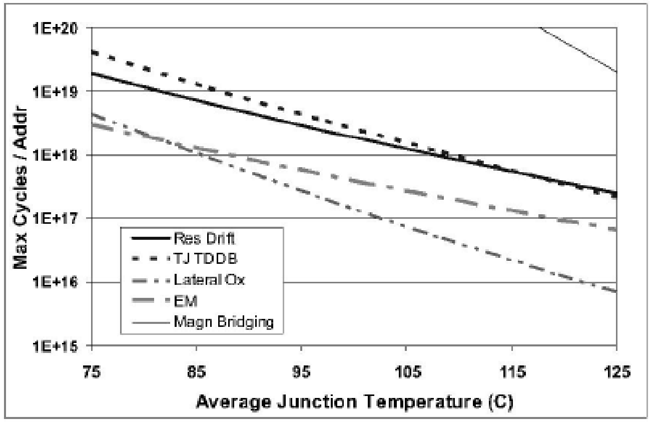
Part Number	**UT8MR2M8**	**UT8MR8M8**
SMD#	5962-12227	5962-13207
Density	16Mb	64Mb, MCM
Interface	Asynchronous SRAM	
Configuration	2M x 8 bit	8M x 8 bit
Supply Voltage	+3.3V	
Access Time	45ns/45 ns (read/write)	50ns/50ns (read/write)
Write Endurance	Unlimited cycles > 20 years	
Data Retention	20 years	
Process Technology	180nm LP TSMC	
Temp Range	-40°C to 105°C	
Typical Power[1]	~10mW/MHz (read)	~15mW/MHz (read)
Package	40 pin CFP, 25 mil pitch 40 pin CFP, 50 mil pitch	64 pin CFP, 50 mil pitch
Operational Environment		
TID:	1Mrad(Si)	
SEL:	112 MeV-cm²/mg @105°C	
SEU:	112 MeV-cm²/mg @25°C	
Qualifications	QML-Q, -V	

[1]Nominal voltage at room temp

Reliability Evaluation

QML-V Qualification and Reliability Demonstration

- Cobham re-validated activation energies and expanded models
- Cobham added reliability mechanism specific burn-in screens to flow
- Cobham extended lifetime projections to > 15 years



Select Subset of Evaluated Wear Out Mechanisms

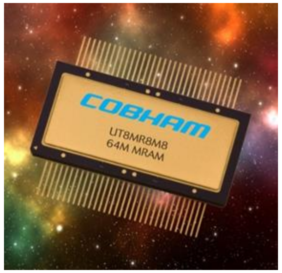
Mechanism	Method	Results	Data
Gate Oxide Integrity (core)	Constant Voltage TDDB	> 15 yr life	< 1 PPM
Gate Oxide Integrity (IO)	Constant Voltage TDDB	> 15 yr life	< 20 PPM
Hot Carrier Integrity (core)	Vd-accel Idsat Degradation	> 15 yr life	<0.1% shift
Hot Carrier Integrity (IO)	Idsat Degradation	> 15 yr life	<10% shift
NBTI	Constant Voltage Bias	> 15 yr life	<10% shift
Electromigration (CMOS)	Constant Current Stress	> 15 yr life	<1 PPM
Electromigration (MRAM)	Constant Current Stress	> 15 yr life	<1 PPM
Tunnel Barrier Integrity	Constant Voltage TDDB	> 15 yr life	<1 PPM
Bias-Driven Resistance Drift	Constant Voltage Bias/ High Temperature	> 15 yr life	< 1000 FIT
Thermal Resistance Shift	High Temperature Bake	> 15 yr life	< 1000 FIT
Magnetic Layer Integrity	High Temperature Bake	> 15 yr life	<0.1% shift
Data Retention	High Temperature Bake	> 20 yr life	<1 PPM

M. Durlam *et al.*, "Toggle MRAM: A highly-reliable Non-Volatile Memory," *2007 International Symposium on VLSI Technology, Systems and Applications (VLSI-TSA)*, Hsinchu, 2007, pp. 1-2.

Status of Cobham MRAM

Timeline of MRAM introduction in Space Applications

- MRAM transition from emerging to mainstream



Eroica	Eagle	GONETS D1M SSR	LCDR	ORION	Parker Solar Probe
AC5	EMM0 SBC & SSR	H2SAT	LEON Link	ORS-5 (SensoSat)	Solar Probe (SOLOHI)
AMOS6	EMP	HIS	LEOSTAR 3	OTOS	SPP
APES	ERLA	HRS IRAD	Lumen	OVIRS-REX	KOMPSAT 6
ATA Dynpak	ESAIL	Hydra	Lumen	P992 Classified	SQDRt
beacon test model	EuCropis	IASI NG (METOP)	Magnus	Poseidon 4	SQRT
CAS500 (GNSs)	EUROPA	ICON (SSP)	MARS	Proba3	SSCO
Channelizer	Europa, EGNS	IRAD	MARS2020, Moxie	R480	SSPD Restore L
Classified	Eval (qual)	IRAD	MEV	R480 (Classified)	SSUSI
Classified	EXOMARS	IRAD	MoPD	RDAU for MEV	STARMU
Classified	Exomars;CaSSIS	IRAD control board	Mustang	Reliant Eye	STPlan
Classified Zipor	Express-AMU2	IRAD SSCO	NavCam	RESTORE REU RSTR	STPSat6
Core Electronics	Facebook Connectivity	ITRS	NEPP	RHBD	SUPERCOM
CORESAT	Formosat-7	Jovian (PEP-HI)	New/Unknown	RS-25	TBD
COTS-PDU CBE EDUS	GBD3	JUICE	Next Gen(Gov't Program)	SARAH	TSIS
CPP Program	GEDI Digitizer	JUICE	NG project	SGRTC	Tuscany
Cypro	GEO ROBOTICS	JUICE DPU	NISAR SSR	SIGHTS	Unknown
DOT	GEO-IK-2	Kittyhaw	Novasar	Solar Orbiter	US Gov't Classified
Draco	Glonass-K	Landsat	OceanSAT II	Solar Orbiter	WASP
Dreamchaser	GONETS D1M	Landsat9	OCI PACE sat	Solar Orbiter (METIS)	WFIRST

- First launches 3/14/16 (EXOMARs, OSIRIS-REX)
- 144 Design In's, 71 Customers

2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020

- Cobham 64Mb MRAM QML-V qualified (1/08/2016)
- Cobham 16Mb MRAM QML-V qualified (12/22/2015)
- Cobham 16Mb MRAM QML-Q qualified (3/25/2014)

Qualification of Emerging Technologies

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Continuous Improvement Applied to Reliability

- Is a standard QML-V qualification flow adequate for emerging technologies?

- Must Evaluate …
  - Are there interactions between failure mechanisms?
  - Did intrinsic “bulk” property analysis comprehend full population?
  - How can process variation learning be accelerated?
  - Develop techniques to expose new mechanisms
  - Refine rationale behind specification limits
  - Refinement of process, screens, flows
  - Quantification of risk

How do we learn the answers to questions we don’t yet know to ask?

Case Study … End of life accelerated HTOL testing on product

Continuous Improvement & Reliability

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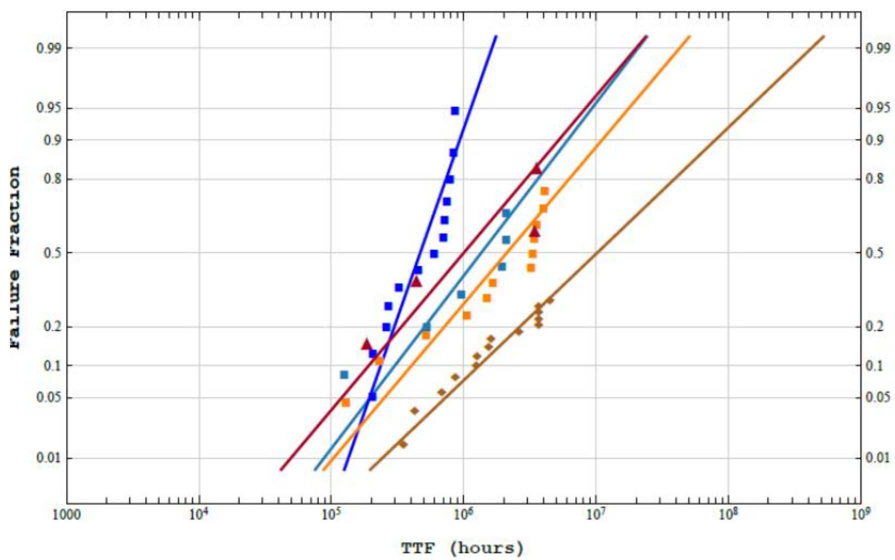
120,000 Hour Equivalent (EOL) Accelerated Stress – Reliability Growth

- Accelerated HTOL used to develop device wear out models
- Data used to determine guard bands at final test
- 60 worst case devices selected from 4 contemporary lots
- Additional 22 devices from original QML-V qual lot
- End of Life FIT rates (to internal <u>ECC-off</u> test limit) determined
- Post-stress Testing
  - All devices pass to all Data Sheet specs at EOL
  - No (ECC-on) failures at EOL or any read point

ECC–off Internal Test Limit Failure Fraction by Lot



Internal <u>ECC-off</u> EOL Limit FIT Rate

Lot No.	Avg. FIT Rate
Lot A	67.7
Lot B	122.3
Lot C	455.3
QML-V Lot	180.5
Lot D	25.5

Continuous Improvement Quantifies and Validates QML-V Qualification

Summary

MRAM and Reliability of Emerging Technologies

- Cobham MRAM introduced at QML-Q level in 2014
  - TID hardened to >1Mrad(Si)
  - SEL Immune (100 MeV·cm^2/mg)
  - SEU immune (100 MeV·cm^2/mg)
- Reliability of an emerging technology can be enhanced through:
  - Thorough physics of failure characterization
  - "Design for Radiation" and "Design for Reliability" techniques
  - Screening coupled with understanding of mechanisms
  - A "Continuous Improvement" methodology approach
  - Accelerated lifetime characterization of product

?