Non-Volatile RAM
for the Internet of Things (IOT)

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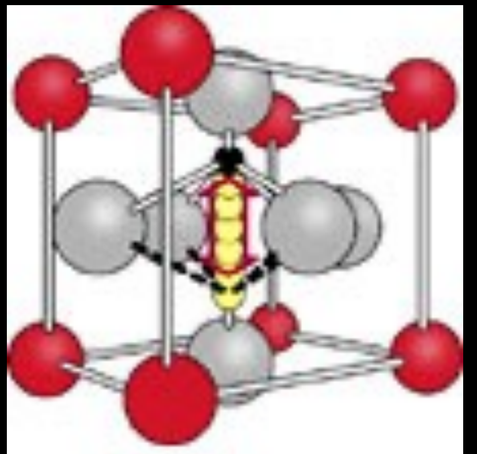
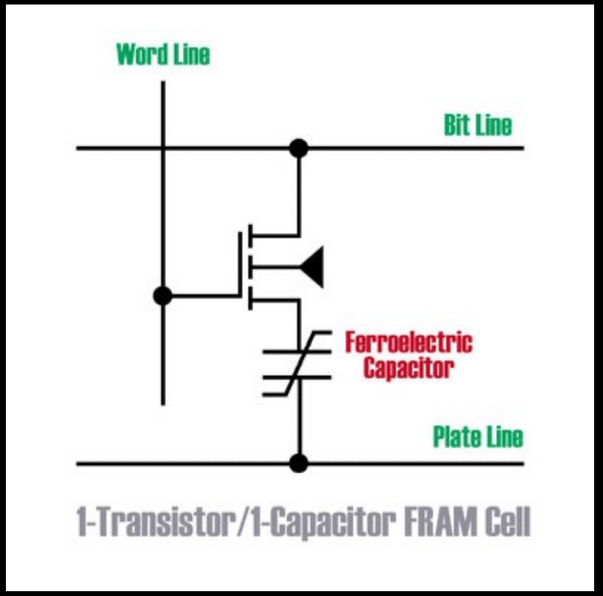
Ferroelectric RAM (FRAM)

- **Certain Ceramic Material Are Polarized By An Electric Field (Ferroelectrics)**
  - KNO_3 - Potassium Nitrate
  - PZT - Lead Zirconate Titanate
  - SBT (Y1) - Strontium Barium Titanate
- **A Ferrocapacitor is Two Metal Plates with Ferro Dielectric**
- **Ferroelectric RAM (FRAM) is DRAM With Ferrocapacitor**
  - Simple 1T-1C Cell Structure like DRAM
  - Low Standby and Active Power
  - DRAM Read/Write Speed (55 ns access, 110 ns Cycle Time)
  - Virtually Unlimited Endurance ($10^{10\text{-}15}$ Cycles)
  - Non-volatile - 10 Year Data Retention without Power
  - Wide Temperature Range (Commercial, Industrial, Automotive)
  - Resistant to Radiation, Electric & Magnetic Fields

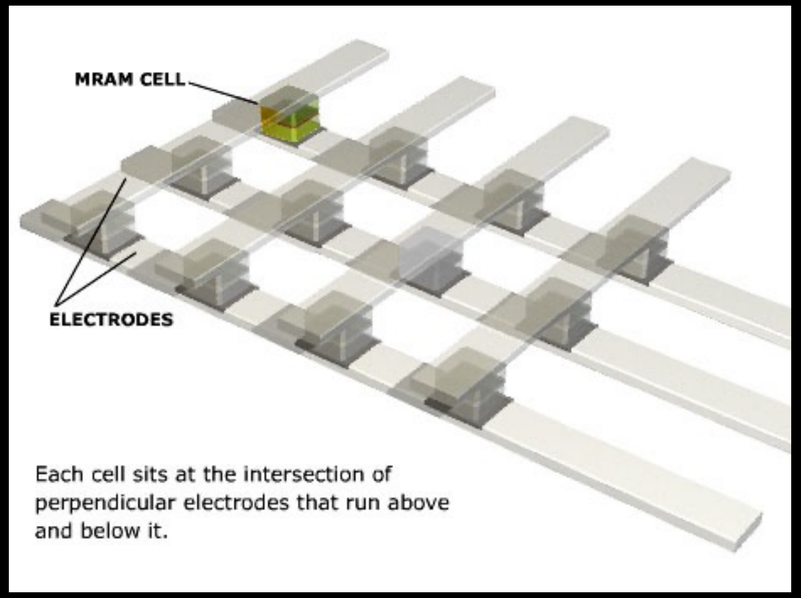


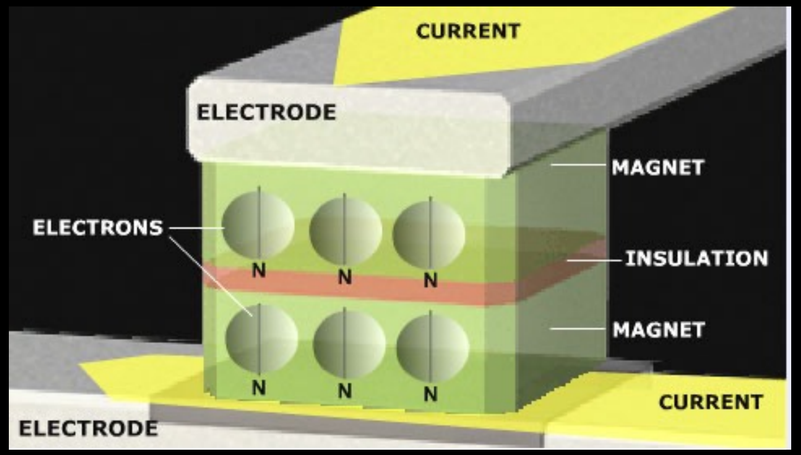


Magnetoresistive RAM (MRAM)

- **Ferromagnetic Memory On Silicon**
  - Concurrent Current From X and Y Lines Polarize Magnetic Tunnel Junction (MTJ)
  - Non-Destructive Readout By Sensing Variation In Resistance Due To Polarization

- **Nonvolatile RAM**
  - Fast 35 ns Read/Write Speed
  - Unlimited Endurance
  - Long Data Retention
  - Low Soft Error Rates (Lower Than SRAM)
  - Wide Temperature Range (Comm, Ind, Auto)
  - Radiation Hard

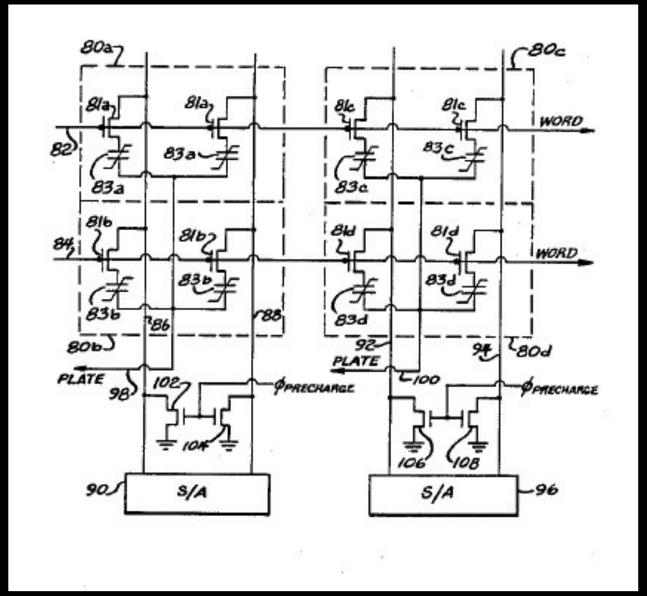




Ramtron International (now Cypress Semiconductor)

- Pioneer In Ferroelectric RAM From 1984
- First FRAM Announced At 1988 ISSCC
- First FRAM 4K Product Announced In 1991
- Owns Key FRAM Patents
- More than 100 million units shipped
- Major FRAM Licensees include TI, Samsung, NEC, Fujitsu, Infineon, Toshiba, Hitachi, Rohm, Asahi
- Acquired By Cypress Semiconductor in 2012

Ramtron HQ in Colorado Springs



Ramtron Patented 1T-1C FRAM Cell

Ramtron Founders

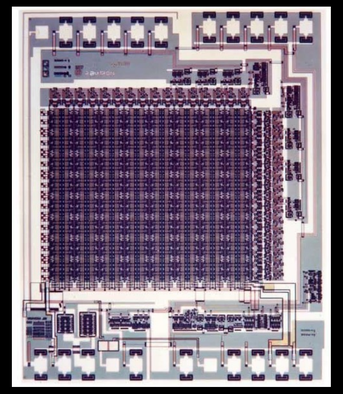
- **Founded by George Rohrer, Larry McMillan, Dr. Carlos Araujo in 1984**
- **Financed By Stock Sale On Australian Exchange**
- **First CEO Was Ross Lyndon-James, Ramtron Australia Ltd.**
- **Rohrer Held The First Ferroelectric Device Patent (1972)**

George Rohrer, Larry McMillan, Ross Lyndon-James on University of Colorado-Colorado Springs Campus

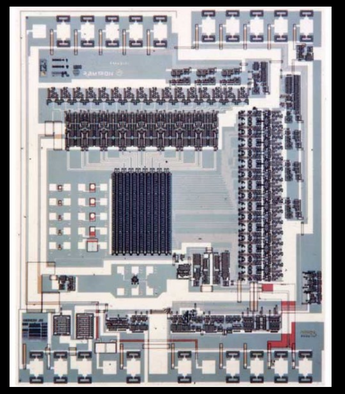
First Ramtron FRAM Devices

- **Early Device Development using KNO_3 Done at UCCS Microelectronic Laboratory starting in 1984**
- **Key Staff Members Join from Colorado Springs DRAM Company Inmos Corporation**
  - **Dr. Fred Gnadinger, VP of R&D**
  - **Sheffield Eaton, Lead FRAM Designer**
- **Device Focus Shifts to PZT - Lead Zirconate Titanate**
- **Ramtron Partners with ITT Semiconductor (Freiburg, Germany)**
- **First 256b FRAM Shown at ISSCC 1988**
  - 10T Shadow RAM (FMx801)
- **First 256b 2T2C FRAM Shown at ISIF 1989**
  - 2T2C (FMx8101)
- **First 4Kb FRAM Shipped To Customers In 1991 (FM1208)**
- **Volume Production of 4Kb FRAM In 1993**

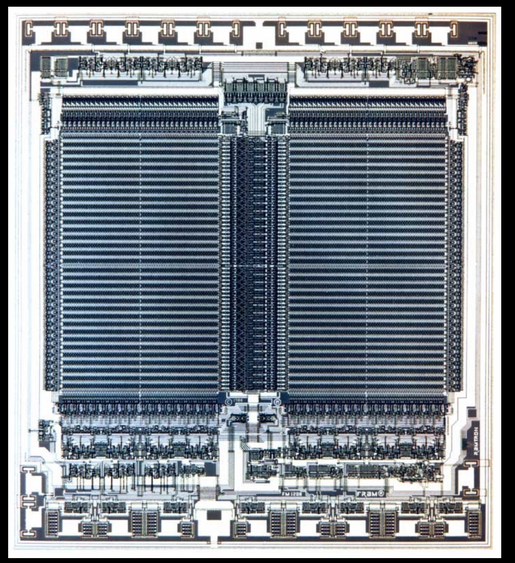
  Sega Genesis Game Cartridges Were the Largest Application



FMx801 10T FRAM



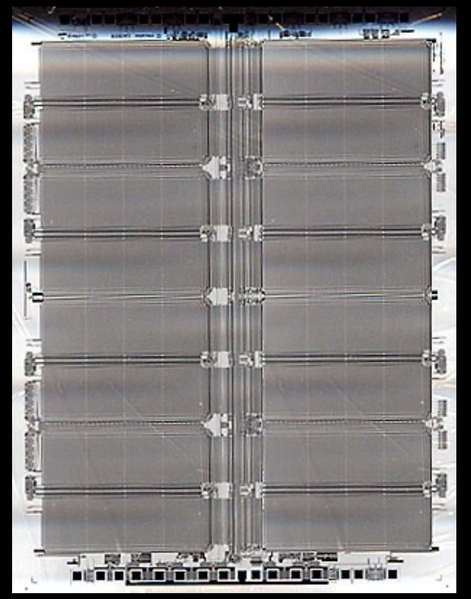
FMx8101 2T2C FRAM



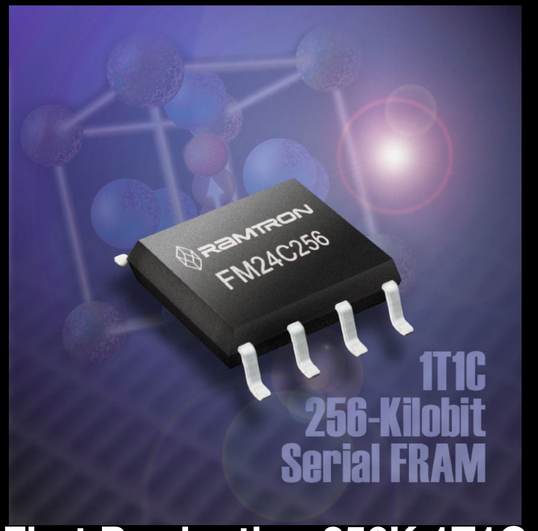
FM1208 4K 2T2C FRAM

Ramtron 1T1C FRAM Development

- Ramtron Partners with Seiko Epson (Japan)
- Seiko Epson Program Yielded First 256Kb 1T1C In 1992
- Ramtron Partners with Rohm Corporation (Japan)
- Rohm (now Lapis Semiconductor) Becomes First FRAM Production Fab
- Ramtron Announces First Serial FRAM & eFRAM Products in 1998
  - 4K & 16K I^2C & SPI FRAM
  - 16Kb RF ID Chip
- Ramtron Partners with Fujitsu Semiconductor
- Ramtron & Fujitsu Described 1Mb 1T1C FRAM In June 1998
- First Production 1T1C FRAM Announced In 2002
  - Main Application is Automatic Electric Meters at ENEL (Italy)
  - 30 million units shipped, 80% of households in Italy



Ramtron/Seiko 256K 1T1C FRAM (1992)

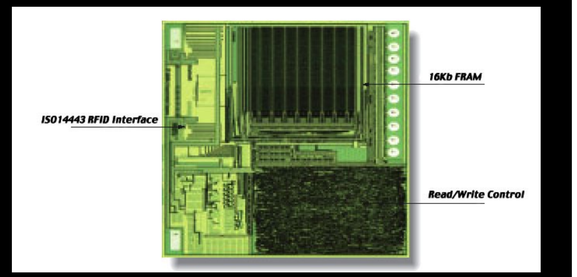


First Production 256K 1T1C Serial FRAM (2002)

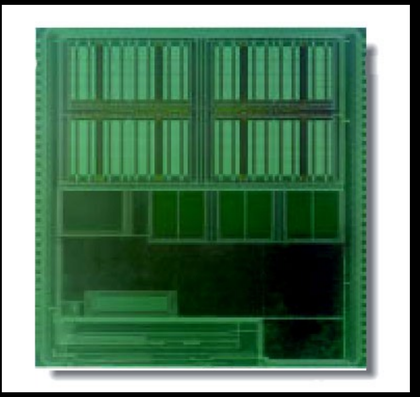
Fujitsu FRAM Program

- **Ramtron Second Production FRAM Fab**
  - 0.5 micron 3LM FRAM Process
  - +5 and +3 volt Operation
  - 2T2C and 1T1C FRAM Cells Supported
  - Densities Up to 1Mb
  - >1 Million/Month 256Kb FRAMs Produced For Ramtron
  - 3 Million/Month eFRAM Smartcards For Fujitsu
- **Next Generation 350 nm Process**
  - 1Mb 1T1C eFRAM at 3 volts
- **Next Generation 180 nm Process**
  - 4Mb & 8Mb 1T1C FRAM & eFRAM at 1.8 Volts

Fujitsu Iwate, Japan FRAM Factory

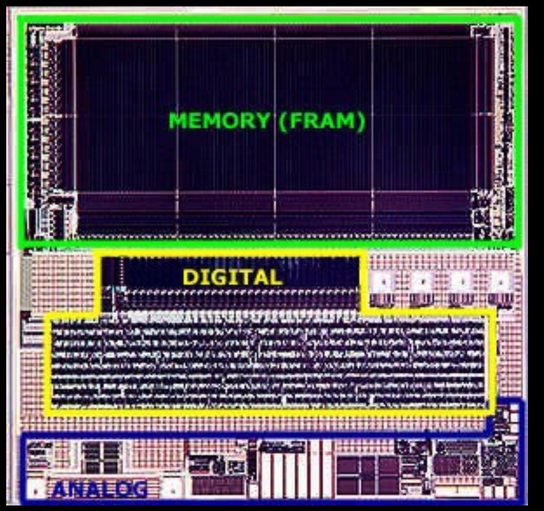


Custom 16Kb RF ID
MB89R111
For Cubic Corp

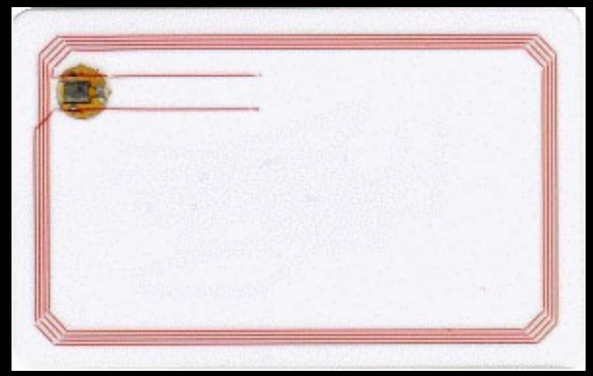


Contacted/Contactless
Smartcard
MB89R202
1Mb FRAM/ARM MCU

Cubic Go Card Program

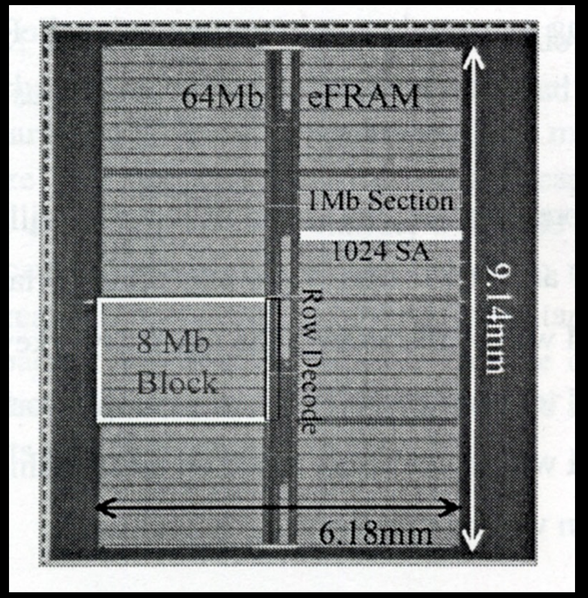


- **Cubic Go Card RF ID**
  - First eFRAM Product
  - 16Kb FRAM+Logic+RF Interface
  - Automatic Fare Collection Card
  - First Built At Rohm, Later At Fujitsu
- **Cubic Uses Go Card In Major Cities**
  - Washington Subway
  - Chicago Transit Authority
  - London Underground
  - Hong Kong Underground

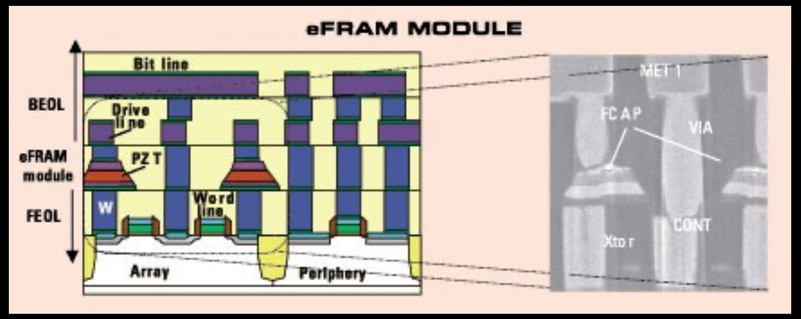


Texas Instruments eFRAM Program

- TI/Agilent/Ramtron Program Started In August 2001
- 64Mb eFRAM Vehicle on 130 nm Process at Kilby Fab in Dallas
- 60 Person Development Team
- 4Mb eFRAM Test Vehicle Described At IEDM 2002
  - +1.5 volt Power Supply
  - 2 Mask eFRAM Process Adder
  - 0.54 um^2 Cell Size ($32F^2$)
  - MOCVD IR/PZT/IR Thin Film FerroCap
  - 40 ns Access
  - >1E12 Endurance Measured
- TI Became Ramtron's 3rd Foundry Partner
- TI Today offers many low-power eFRAM MCU Products based upon this process



64Mb FRAM Test Vehicle



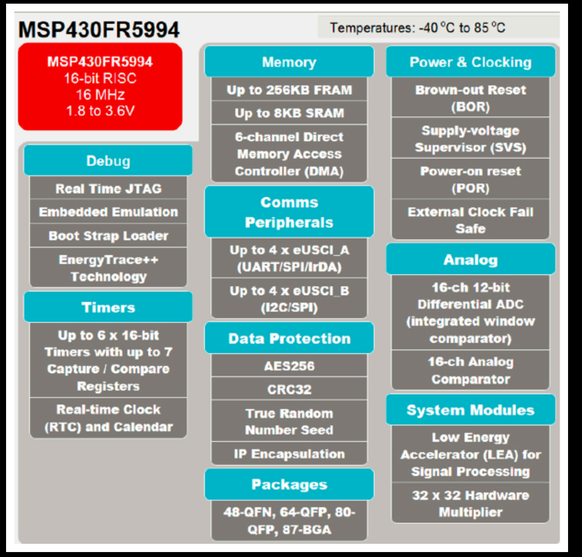
eFRAM Process Cross Section

TI 430 MCU Family

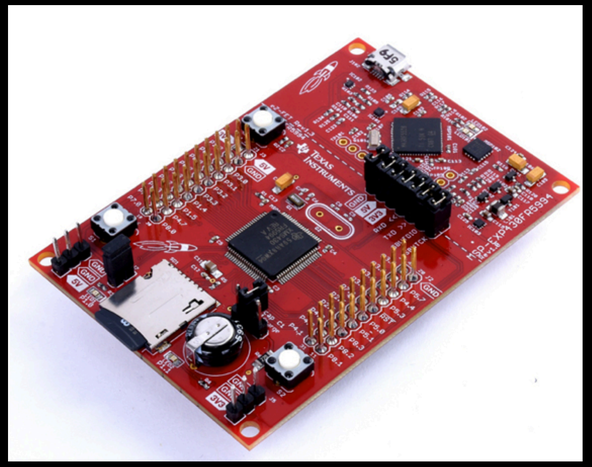
- Texas Instruments has become the leading Off-the-Shelf MCU Supplier offering eFRAM

- FRAM Series MCUs
  - 4 to 256KBytes of eFRAM (10^{15} endurance)
  - 0.5 to 8KBytes of eSRAM
  - 1.8 to 3.6 volt power supply
  - 118 uA/MHz active power
  - 350 na standby with RTC operating
  - 35 na shutdown mode
  - Many I/O Options
  - Many Package Options
  - Commercial & Industrial Temperature

- Why Pick FRAM MCU For IOT Applications
  - Low power for Battery or Energy Harvesting Applications
  - Flexibility of Partitioning Programs & Data in FRAM
  - Easy In Product Software Updates
  - Wide Temperature Range Operation
  - Single Chip Solution in Many Cases
  - Radiation Tolerance for Medical & Food Products Sterilized Using Radiation



TI 430FR5994 Features 256KBytes of eFRAM



LaunchPad Demo System

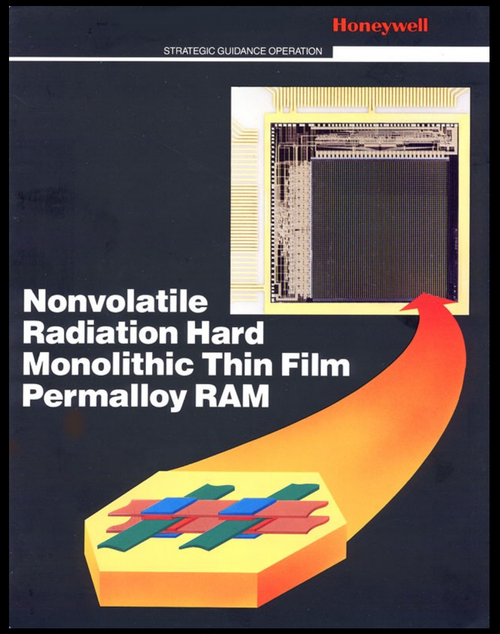
Fujitsu RF ID Products

- Fujitsu offers off-the-Shelf Contactless RF ID Solutions
- Fujitsu offers COT and Custom Development eFRAM options

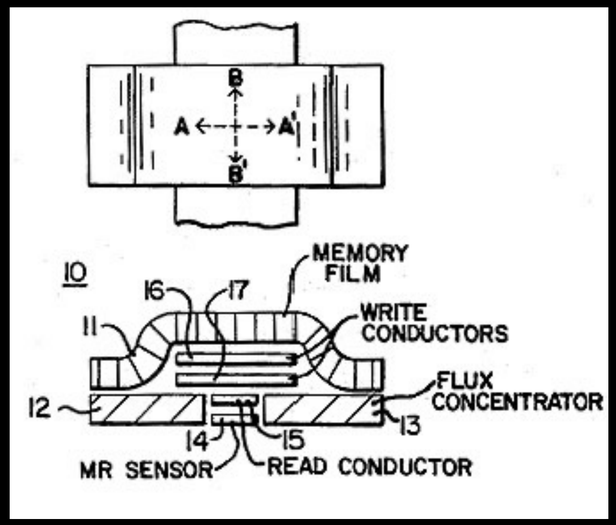
Part Number	Operating Frequency	Memory Density	Commands	Serial Interface	Data Retention Guaranteed	Read/Write Cycles
MB97R803A/B	UHF 860-960MHz	4KBytes	ISO/IEC18000-6C EPC C1G2 Ver.1.2.0	–	10 years (+55°C)	10^{10} (10 billion) times
MB97R804A/B	UHF 860-960MHz	4KBytes	ISO/IEC18000-6C EPC C1G2 Ver.1.2.0	SPI	10 years (+55°C)	10^{10} (10 billion) times
MB97R8050	UHF 860-960MHz	128bits	ISO/IEC18000-6C EPC C1G2 Ver.1.2.0	–	10 years (+55°C)	10^{10} (10 billion) times
MB89R118C	HF 13.56MHz	2KBytes	ISO/IEC15693	–	10 years (+85°C)	10^{12} (1 trillion) times
MB89R119B	HF 13.56MHz	256Bytes	ISO/IEC15693	–	10 years (+85°C)	10^{12} (1 trillion) times
MB89R112	HF 13.56MHz	9KBytes	ISO/IEC15693	SPI	10 years (+85°C)	10^{12} (1 trillion) times

MRAM - Historical View

- **Plated Magnetic Memories Date from 1960 Core Memory**
  - Plated Wire (1970s)
  - Permalloy On Glass (1970s)
  - Permalloy On Silicon (1980s)
- Dr. James Daughton from Honeywell Solid State Electronics Founds NVE Corporation in 1989. Now the Leading Magnetic Sensor Company
- Darpa Funds 3 MRAM Programs in 1995
  - NVE/Cypress
  - Motorola (Freescale)
  - IBM



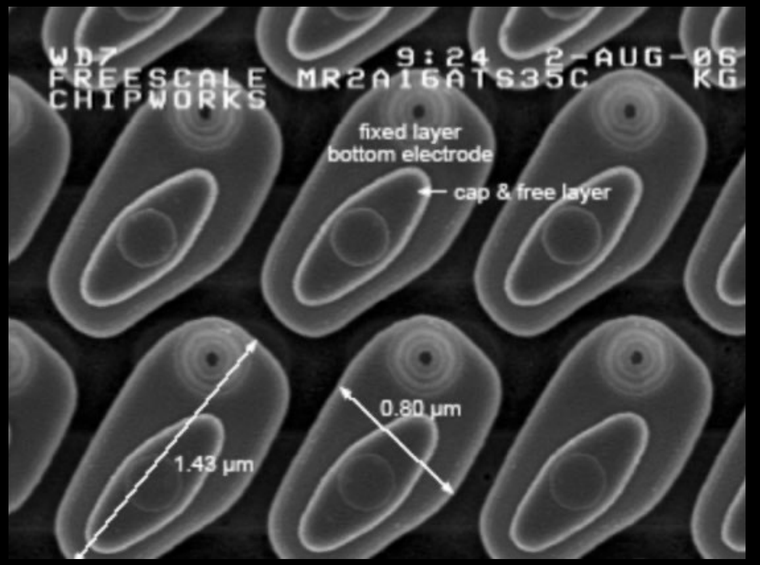
Honeywell 2Kb Peralloy RAM Brochure - 1986



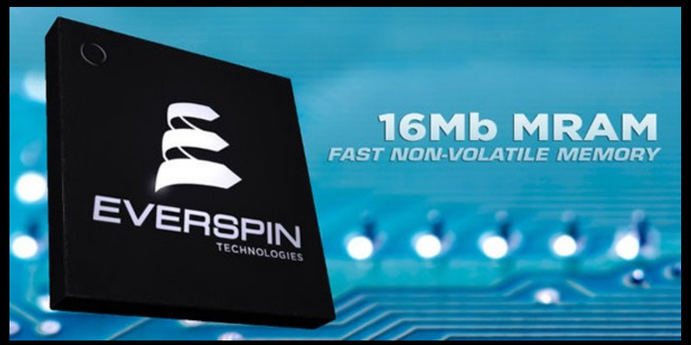
US Patent #4455636
Olin Lutes, Honeywell, Inc. 1983

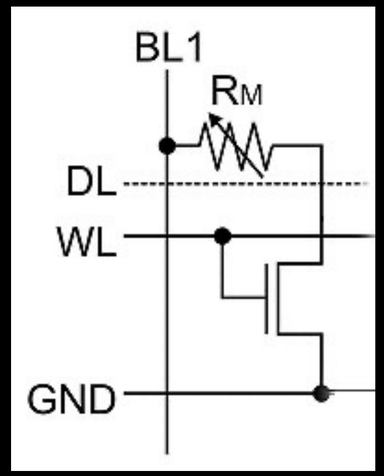
MRAM Development

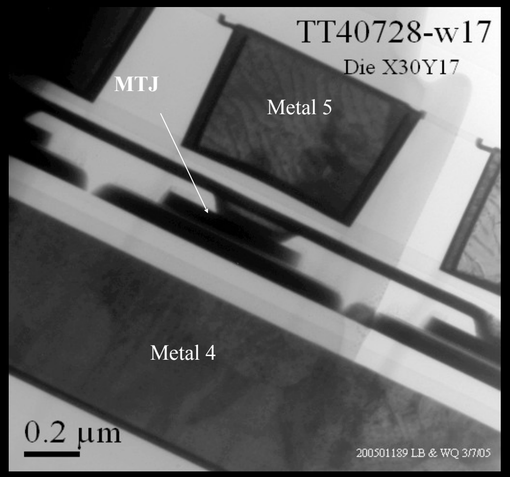
- Freescale Semiconductor (Motorola) Pioneered the Toggle MRAM
  - 256Kb MRAM (2001)
  - 1Mb MRAM (2002)
  - 4Mb MRAM (2004)
  - First 4Mb Production MRAM (2006)
  - First 16Mb MRAM
- Freescale MRAM Business Becomes Everspin Technologies (Nasdaq: MRAM) in 2008
- Everspin offers 8 & 16 bit Parallel MRAM, SPI & QSPI MRAM Products today



Magnetic Tunnel Junction Top View







1T-1MTJ Cell Design, Cross Section

ST-MRAM Development

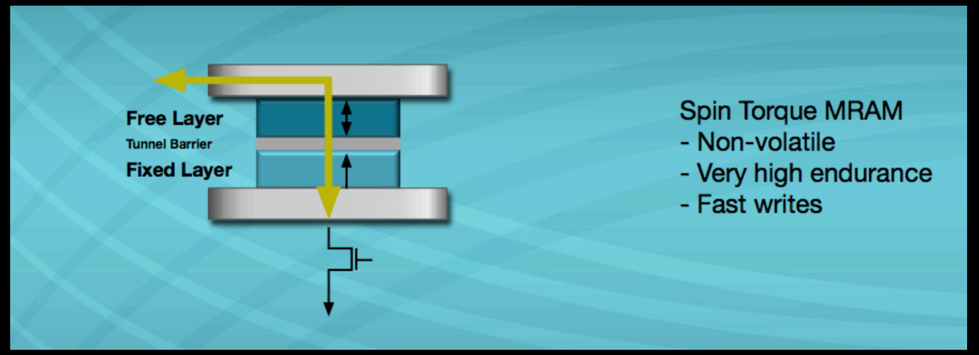
- Spin Torque MRAM writes the MTJ using current through the device barrier. This is done at lower current allowing MRAM scaling to below 22 nm

- In 2008, Grandis was awarded a contract by DARPA to develop STT-MRAM

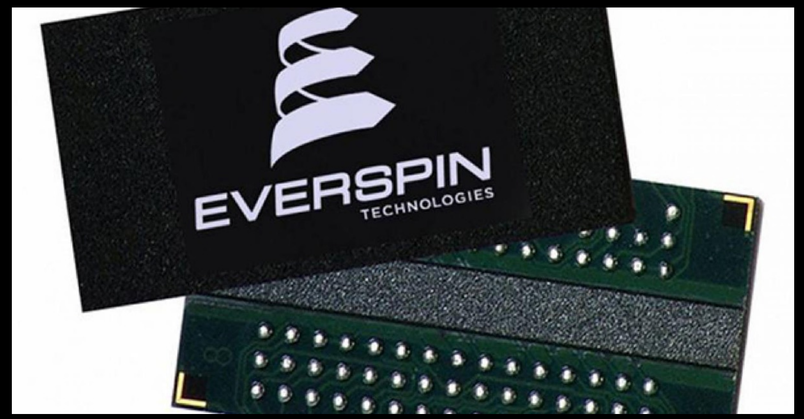
- In 2011, Grandis was acquired by Samsung

- Everspin developed ST-MRAM Products
  - 64Mb DDR3 (2012)
  - 256Mb DDR3 (2016)
  - 1Gb DDR4 (2018)

- Avalanche Technology became second commercial ST-MRAM supplier in 2019
  - 1Mb-16Mb SPI PSRAM (Persistent SRAM)
  - 1Mb-16Mb QSPI PSRAM



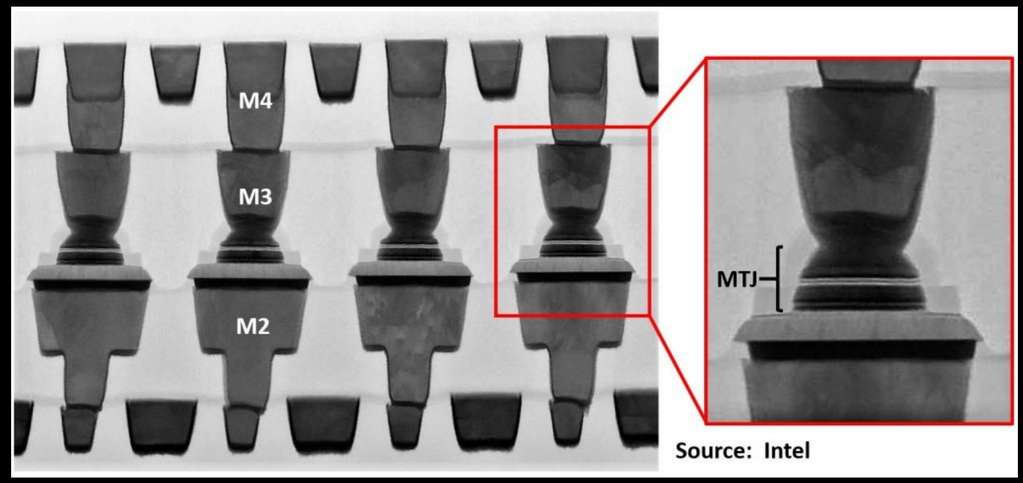
Spin Torque MRAM (ST-MRAM)



First 1Gb DDR4 ST-MRAM (2019)

Emerging ST MRAM Foundry Offerings

- Everspin Technologies announced development of 40, 28, and 22 nm ST eMRAM foundry offerings with Global Foundries (Singapore) in 2017
- Avalanche Technology announced 28 nm eMRAM foundry with UMC (Taiwan) in 2018
- Samsung announced 28 nm eMRAM foundry (Korea) in 2018
- Intel announced 22 nm eMRAM process for their products in 2019
- Gyrfalcon announced Edge AI Processor Chip using 22 nm eMRAM process from TSMC (Taiwan) in 2019
- ST MRAM expected to become mainstream embedded memory alternative to NOR Flash, EEPROM & SRAM



Intel Corporation 22 nm ST eMRAM (2019)

Standalone Non-Volatile RAM Products

- Standalone Non-Volatile RAM Products Available from Cypress (Ramtron), Fujitsu, Lapis (Rohm), Everspin (Freescale), and Avalanche
  - Parallel RAM (64Kb to 1Gb)
  - Serial I2C FRAM (4Kb to 1 Mb)
  - Serial SPI, QSPI FRAM & MRAM (4Kb to 16Mb)

Non-volatile RAM Products (Parallel Interface)

	64Kb (8Kx8)	128Kb (16Kx8)	256Kb (32Kx8)	1Mb (128Kx8)	4MB (512Kx8)	1Mb (64Kx16)	2Mb (128x16)	4Mb (256Kx16)	8Mb (512Kx16)	16Mb (2Mbx8)	16Mb (1Mbx16)	32 Mb (2Mbx16)	256Mb DDR3 ST-MRAM	1Gb DDR4 ST-MRAM
Cypress (Ramtron) FRAM	X		X	X		X	X	X			X			
Fujitsu FRAM			X	X	X	X		X	X					
Lapis (Rohm) FRAM			X											
Everspin MRAM		X	X	X	X	X	X	X	X	X	X	X	X	X

Non-Volatile RAM Products (Serial I2C Interface)

	4Kb	16Kb	64Kb	128Kb	256Kb	512Kb	1Mb	2Mb	4Mb
Cypress (Ramtron FRAM	X	X	X	X	X	X	X		
Fujitsu FRAM	X	X	X	X	X	X	X		
Lapis (Rohm) FRAM			X				X		

Non-Volatile RAM Products (Serial SPI,QSPI)

	4Kb	16Kb	32Kb	64Kb	128Kb	256Kb	512Kb	1Mb	1Mb QSPI	2Mb	4Mb	4Mb QSPI	8Mb	8Mb QSPI	16Mb	16Mb QSPI
Cypress (Ramtron) FRAM	X	X		X	X	X	X	X		X	X	X	X			
Fujitsu FRAM		X		X	X	X	X	X		X						
Lapis (Rohm) FRAM			X	X		X		X								
Everspin MRAM					X	X		X	X		X					
IDT (Avalanche) MRAM								X	X		X	X	X	X	X	X

Software Consideration with Non-Volatile RAM

- NAND Flash Memory Has Significant Software Overhead
  - Limited Endurance Requires Wear Leveling and Block Management
  - Poor Reliability Require Extensive ECC Software
  - Slow Write Speed Essentially Requires Copy in SRAM or DRAM with Write in Background or At Power Down
  - May Lose Critical Data During Power Loss without Backup Supply or Battery
  - Probably not suitable for industrial or automotive temperatures

- NOR Flash Has Similar Difficulty Managing Write Data as NAND Flash
  - Good for data reads, poor for data writes

- EEPROM Provides Random Access Read and Write But
  - Limited Endurance Means Can’t Perform Real Time Writes, Only Periodic Saves
  - 10 mS write speed too slow for real time writing, typically keep copy in SRAM or DRAM
  - May Lose Critical Data During Power Loss without Backup Supply (SuperCAP) or Battery

- FRAM & MRAM provides random access read & writes like SRAM or DRAM
  - High Endurance eliminates concern about write data loss
  - Always non-volatile without backup when power is lost
  - Can map both programs and data into common data space and change dynamically in the field
  - Instant-On, No Boot From Flash to DRAM or SRAM
  - Can have very low power operation for battery powered or energy harvested application
  - Operates over wide temperature & is radiation tolerant

FRAM Application

- Data Logging - Crash Recorders, Video Recorders, Medical Devices
- Metering - Power Meters, Water Meters, Gas Meters
- Battery Powered or Energy Harvesting Applications - RF ID, NFC Chips, Contactless Smartcards,
- Medical Applications Requiring Radiation Sterilization
- Small Single Chip Systems Where FRAM Becomes Consolidated Program & Data Storage - Smoke Detector, Thermostats, Smart Locks, Motion Detectors

MRAM Applications

- Enterprise Data Storage - Write Buffers, Meta Data Storage, Index Memory
- Industrial, Automotive, Avionics & Space Applications - Wide Temperature Range, Lower Soft Error Rate, More Reliable Than Flash
- Instant-On Systems - No Need to Boot Data from Flash to DRAM or SRAM
- Medical Systems - Fast Data Logging, Data Never Lost During Power Fail
- Replace SRAM, NOR Flash, EEPROM in future single chip MCU Systems
- Replace Large Cache in High Performance Multiprocessor Systems
- Distributed Persistent Memory for AI Systems