eMRAM: From Lab to Fab
CEA-Leti Memory Workshop 2017
June 27, 2017
Dave Eggleston, VP Embedded Memory
High Volume New Markets Driving the Opportunities

All data, except for 5G, refer to 2020. Sources: 5G: Mobile Experts; Automotive and Mobility: Average of IHS and other market research firms' data; AR/VR: GLOBALFOUNDRIES analysis of Goldman Sachs, Bank of America, and some market research data; Commercial Drones, Data Centers, and IoT: GLOBALFOUNDRIES analysis and interpretation of market research data; Robotics: GLOBALFOUNDRIES analysis of Bank of America and some market research data.

CLIENTS

- Automotive
- IoT
- Mobility

NETWORKS

- Wired / Wireless

DATA CENTERS

- Compute / Clouds

MOBILITY

- Devices: $339B
- Semi content: $100B

AUTOMOTIVE

- Electronics: $170B
- Semi content: $42B

IoT

- Endpoints / service: $506B
- Semi content: $34B

5G

- 2025 Infrastructure: $20B
- 2025 Semi content: $6B

DATA CENTERS

- Systems: $62B
- Semi content: $26B

ROBOTICS

- Hardware / software: $83B
- Semi content: $8B

AR / VR

- Hardware / software: $80B
- Semi content: $9B

COMMERCIAL DRONES

- Personal drones: $5B
- Semi content: $1B

AR / VR

- 2025 Infrastructure: $20B
- 2025 Semi content: $6B

All data, except for 5G, refer to 2020.
High Volume New Markets Driving the Opportunities

**CLIENTS**
- Mobility
- IoT
- Automotive

**DATA CENTERS**
- Compute / Clouds

**NETWORKS**
- Wired / Wireless

**MOBILITY**
- Devices: $339B
- Semi content: $100B

**AUTOMOTIVE**
- Electronics: $170B
- Semi content: $42B

**IoT**
- Endpoints / service: $506B
- Semi content: $34B

**5G**
- 2025 Infrastructure: $20B
- 2025 Semi content: $6B
- Systems: $62B
- Semi content: $26B

**ROBOTICS**
- Hardware / software: $83B
- Semi content: $8B

**AR / VR**
- Hardware / software: $80B
- Semi content: $9B

**COMMERCIAL DRONES**
- Personal drones: $5B
- Semi content: $1B

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
Embedded Memory: Non-Volatile Options

- eFlash
- eMRAM
- PCM
- CNT
- eRRAM
- FeFET

Retention  Efficiency  Speed
Embedded Memory: Non-Volatile Options

- **eMRAM**
  - Pro: speed, endurance, versatility, masks
  - Con: complex stack, data retention

- **eFlash**
  - Pro: data retention
  - Con: speed, masks

- **eRRAM**
  - Pro: simple stack, masks
  - Con: speed, endurance, data retention

- **CNT**
  - Immature

- **FeFET**
  - Immature

- **PCM**
  - Not (yet) Suitable for eNVM
Embedded Memory: <28nm Application View

- Automotive
- MCU
- IoT
- Storage
- Compute

eMRAM?

Retention  Efficiency  Speed

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
Embedded Memory: eMRAM market timing

- Automotive
- MCU
- IoT
- Storage
- Compute

Sooner eMRAM

Retention  Efficiency  Speed

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
Embedded Memory: eMRAM markets
## Embedded Memory: eMRAM market requirements

<table>
<thead>
<tr>
<th></th>
<th>Automotive</th>
<th>MCU</th>
<th>IoT</th>
<th>Smartcard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temperature</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low/Med</td>
</tr>
<tr>
<td>Solder Reflow Retention</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Magnetic Immunity</td>
<td>Medium</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
eMRAM Limitations
eMRAM Technical Barriers

Operating Temperature
- Small memory window (TMR)
- Larger/complicated sense amp;
  Slower read speed

Solder Reflow Retention
- 260°C, 5 min data retention
- Must raise Eb, without increasing bitcell size
- Difficult challenge; requires tradeoffs

Magnetic Immunity
- New issue unique to magnetic memory
- 500 Oe – 1000 Oe (100mT) without shielding
- Customer specs still evolving

© 2017 GLOBALFOUNDRIES/CEA-Leti 2017
CMOS-embedded STT-MRAM Arrays in 2x nm Nodes for GP-MCU applications

D. Shum1,*, Sr. Member, IEEE, D. Houissameddine1, S.T. Woo1, Y.S. You1, J. Wong1, K.W. Wong1, C. Yamane1, V.B. Naik1, C.S. Seet1, T. Tahmasebi1, C. Hai1, H.W. Yang1, N. Thiyagarajah1, R. Chandra1, J.T. Ling1, T.H. Chan1, S.Y. Sial1 and R. Nair1

1GLOBALFOUNDRIES Singapore Pte. Ltd., Singapore, 738406. *Phone: +65-66702800, Fax: +65-66702839, Email: D.Shum@GLOBALFOUNDRIES.com

S. Deshpande2, R. Whig2, K. Nagel2, S. Aggarwal2, M. DeHerrera2, J. Janesky2, R. S. DeNardi2, R. H. Lu2, S. Ikegawa2, F.B. Mancoff2, G. Shimon2, J.M. Slaughter2, J.J. Schler2, M. Deherrera2, and F. Andre2

2Everspin Technologies, Inc., Chandler, AZ 85225, USA. *Phone: +1-480-872-2411, Fax: +1-480-872-5100, Email: D.Shum@GLOBALFOUNDRIES.com

© 2017 GLOBALFOUNDRIES/CEA Leti 2017

Paper now available for download at: https://www.globalfoundries.com/technology-solutions/cmos/embedded-memory

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
Embedded Memory: eMRAM capabilities

- **Automotive**: High, Yes, Medium
- **MCU**: Medium, Yes, Medium
- **IoT**: Medium, No, Medium
- **Smartcard**: Low/Med, No, Medium

- **Operating Temperature**: High, Medium, Medium, Low/Med
- **Solder Reflow Retention**: Yes, Yes, No, No
- **Magnetic Immunity**: Yes, Yes, No, High

= Capable = Not Capable

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
Embedded Memory: eMRAM capabilities

Automotive

MCU

IoT

Operating Temperature

Tj=125°C (grade 2); grade 1 TBD

260°C, 5 minutes

Magnetic Immunity

100mT, non-operating

Solder Reflow Retention

260°C, 5 minutes

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
Embedded Memory: non-eMRAM Opportunity

- Smartcard: Capable
- Operating Temperature: Low/Med
- Solder Reflow Retention: No
- Magnetic Immunity: High

eRRAM, CNT, FeFET
eMRAM Enabling Features
Differentiation using Design

- eMRAM: Two functions on the same wafer
  - By varying the cell configuration and macro design, both code/data storage and working data functions are achieved!
Versatility of eMRAM enhances Architecture

Architecture
- Change around eMRAM
- Both code and data/state
- Great for normally-off systems

Energy Savings
- New ultra-efficient memory subsystem
- Power cycle without time or energy penalty
- 1/3\textsuperscript{rd} power of standard SOC
<table>
<thead>
<tr>
<th></th>
<th>eFlash</th>
<th>eMRAM (macro#1)</th>
<th>eMRAM (macro#2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed (Rd/Wr)</td>
<td>10ns / 20us</td>
<td>25ns /200ns</td>
<td>12.5ns /40ns</td>
</tr>
<tr>
<td>Cell size</td>
<td>40F^2</td>
<td>45F^2</td>
<td>70F^2</td>
</tr>
<tr>
<td>Endurance</td>
<td>10^5</td>
<td>≈10^8</td>
<td>≈10^10</td>
</tr>
<tr>
<td>Data Retention</td>
<td>&gt;20 years</td>
<td>10 years</td>
<td>10 years</td>
</tr>
<tr>
<td>Solder reflow (260C/5min)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Op Temp (Tj)</td>
<td>155C Auto grade 1</td>
<td>125C Industrial/ Auto grade 2</td>
<td>125C Industrial/ Auto grade 2</td>
</tr>
</tbody>
</table>
Competing Solutions
eMRAM competing solutions

- eRRAM, CNT, FeFET
- eMRAM
- eFlash
- SIP Flash

TTM = Time To Market

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
eMRAM vs. eFlash vs. SIP Flash

- Memory Price/Mb
- SRAM size
- Read Latency/Speed
- Energy
- Write speed/Endurance
- Data Retention
- Memory Capacity

Outer ring: Better
Inner ring: Worse

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
eMRAM Commercial Barriers

Capital Equipment
- Expensive, unique eMRAM CapEx
- Deposition, etch, magnetic anneal

Throughput and Yield
- Must achieve 20+ wph
- Must achieve typical 95%+ yield; <1E^-6 RBER

Customers
- Will not pay for write speed/endurance benefits
- Want a cost reduction vs. eFlash
- Taking a schedule and reliability risk

“Still a desire for higher throughput and lower complexity/cost”

As an industry, we are not there yet!
Future eMRAM
Embedded Memory: eMRAM types
Embedded Memory: eMRAM types

Automotive  MCU  IoT  Storage  Compute

Retention  Efficiency  Speed

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
Embedded Memory: eMRAM types
<table>
<thead>
<tr>
<th></th>
<th>eFlash</th>
<th>eMRAM-F (macro#1)</th>
<th>eMRAM-F (macro#2)</th>
<th>eMRAM-S</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Speed (Rd/Wr)</strong></td>
<td>10ns / 20us</td>
<td>25ns /200ns</td>
<td>12.5ns /40ns</td>
<td>≈ 5ns / 10ns</td>
</tr>
<tr>
<td><strong>Cell size</strong></td>
<td>40F²</td>
<td>45F²</td>
<td>70F²</td>
<td>100-120F²</td>
</tr>
<tr>
<td><strong>Endurance</strong></td>
<td>10⁵</td>
<td>≈10⁸</td>
<td>≈10¹⁰</td>
<td>≈10¹⁴</td>
</tr>
<tr>
<td><strong>Data Retention</strong></td>
<td>&gt;20 years</td>
<td>10 years</td>
<td>10 years</td>
<td>1 month</td>
</tr>
<tr>
<td><strong>Solder reflow</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>(260°C/5min)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Op Temp (Tj)</strong></td>
<td>155°C Auto grade 1</td>
<td>125°C Industrial/ Auto grade 2</td>
<td>125°C Industrial/ Auto grade 2</td>
<td>105°C Enterprise</td>
</tr>
</tbody>
</table>
How much Endurance is enough for eMRAM-S?

Systematic Validation of 2x nm Diameter Perpendicular MTJ Arrays and MgO Barrier for Sub-10 nm Embedded STT-MRAM with Practically Unlimited Endurance

J.J. Kan¹,a, C. Park¹, C. Ching², J. Ahn², L. Xue², R. Wang², A. Kontos², S. Liang², M. Bangar², H. Chen², S. Hassan², S. Kim¹, M. Pakala²,b, and S. H. Kang¹

¹Qualcomm Technologies, Inc., San Diego, California 92121, USA. E-mail: aikan@qti.qualcomm.com
²Applied Materials, Inc., Sunnyvale, California 94085, USA. E-mail: bmahendra_pakala@amat.com

For typical cache use cases, an average time exists between successive writes to the same cache block. From reported workload simulations, very write-intensive applications (> 50% write vs. read) have a median write interval of ~ 10 ms (20% of bits have Δt ≥ 40 ms) [4]. This implies that a write endurance of $10^{11}$ cycles would be sufficient for 30 years of uniform write operations. Alternatively, one could assume a 32 MB STT-MRAM (64-bit I/O, 5 ns write cycle time) subjected to a constant write traffic of 1.6 GBps. With uniform writing, a lifetime of 63 years would be expected for an endurance of only $10^{11}$ cycles, substantially less than the $10^{15}$ predicted for our worst 1 ppm.

“Write endurance of $10^{11}$ cycles would be sufficient for 30 years of uniform write operations”
Future eMRAM

- Gb densities of NV memory
  - Enables real-time analysis of big data

- Powers intelligent clients
  - AR/VR, AI, Autonomous Vehicles

- NV-logic transformation
  - Integrate non-volatility directly into logic elements
Building Global Scale for FDX™

Dresden, Germany Fab 1
- Expanding 22FDX® FD-SOI capacity by 40% by 2020
- Developing 12FDX™ FD-SOI technology with tape-outs 2H 2018

Chengdu, China Fab 11
- New 300mm fab in partnership with Chengdu Municipal Government
- Existing 180/130nm technologies, production starting 2H 2018, then 22nm in 2H 2019

- Multi-fab sourcing for assurance of supply
- Multiple substrate vendors for robust supply chain
- Local commitment to China industry growth

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
FD-SOI Will Become Standard for the Volume Tier

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Intel</td>
<td></td>
<td></td>
<td></td>
<td>14nm</td>
<td>14nm+</td>
<td>10nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FinFET</td>
<td>FinFET</td>
<td>FinFET</td>
<td></td>
</tr>
<tr>
<td>GF</td>
<td>28nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAMSUNG</td>
<td>28nm</td>
<td>20nm</td>
<td>14nm</td>
<td>28nm</td>
<td>10nm</td>
<td>7nm</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>FinFET</td>
<td>FinFET</td>
<td>FinFET</td>
<td>EUV</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>20nm</td>
<td>FDSOI</td>
<td>14nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>BEOL</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SMIC</td>
<td>28nm</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TSMC</td>
<td>20nm</td>
<td>16nm+</td>
<td>10nm</td>
<td>7nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FinFET</td>
<td>FinFET</td>
<td>FinFET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20nm</td>
<td>16nm</td>
<td>10nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UMC</td>
<td>28nm</td>
<td></td>
<td></td>
<td>14nm</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FinFET</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>20nm</td>
<td>BEOL</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Source: Companies, conference reports, IC Insights

- Camera
- Computer Graphics
- NLP
- AR / VR
- Natural Interfaces for Input
- Real-time data processing
- Connectivity

© 2017 GLOBALFOUNDRIES/ CEA Leti 2017
GLOBALFOUNDRIES CMOS Roadmap

**Markets:**
- High Performance Computing: Servers, high performance computing and graphics, high-end smartphone, core networking
  - Premium Tier Features: High-performance, balanced-cost
  - Volume Tier Features: Low-power, cost-effective-performance, RF, embedded memory
- Wireless, Battery-Powered Computing: Low & mid-end smartphones, wireless, IoT, autonomous vehicles, mobile camera

**Markets:**
- Low & mid-end smartphones, wireless, IoT, autonomous vehicles, mobile camera

**Features:**
- eMRAM-S: 7nm FinFET
- eMRAM-F: 12FDX™
- 14nm FinFET
- 22FDX®
- 28nm
- 40/55nm

© 2017 GLOBALFOUNDRIES/CEA Leti 2017
GLOBALFOUNDRIES and Everspin continue to drive embedded MRAM (eMRAM) forward into the 22nm process node!

For the first time, we are unveiling eMRAM that can retain data through solder reflow at 260C and 10+ years at 125C, plus read/write with outstanding endurance at 125C.

This is a major breakthrough from GLOBALFOUNDRIES and Everspin that enables eMRAM to be used for general purpose MCU's and Automotive SOCs.

Please contact me if you want more information! dave.eggleston@globalfoundries.com
Embedded Memory
Solving your product challenges for the hyperconnected world