Conductive-bridge Memory (CBRAM®) with Excellent High-temperature Retention and Tolerance to High Levels of Gamma Radiation

Dr. Venkatesh P. Gopinath, V.P. of CBRAM Technology
Adesto Technologies
Outline/Contents

• Introduction to Adesto Technologies

• Introduction to CBRAM

• CBRAM from Adesto®
  – General characteristics
  – High-T retention
  – Radiation tolerance

• Conclusions
Adesto Technologies Corporate Overview

Overview:
Private company founded in 2007 by semiconductor industry veterans

Locations:
Headquarters in Silicon Valley, California / Offices in Asia, Europe

Employees:
100 (Engineering=70, Sales/Marketing=20, Other=10)

Status:
$50M+ profitable business, supporting over 100 tier 1 customers

Business Model:
Discrete product manufacturing and technology licensing

Technologies:
Serial Flash / DataFlash® / CBRAM®
Solid Intellectual Property Position: Over 100 patents granted or filed
Outline/Contents

• Introduction to Adesto Technologies

• Introduction to CBRAM

• CBRAM from Adesto
  – General characteristics
  – High-T retention
  – Radiation tolerance

• Conclusions
Moore’s Law

![Graph showing the trend of device dimensions over time with different technologies like KrF, ArF, ArF + immersion, Double Patterning, EUV, NAND, and Logic. The x-axis represents the year (1995 to 2020), and the y-axis represents the device dimension in nanometers (nm). The graph illustrates the evolutionary path of semiconductor technology as per Moore's Law.](image-url)
Candidates for Next Generation NVM

- Ferroelectric RAM (FeRAM)
- Magnetic RAM (MRAM)
- Phase Change Memory (PCM)
- Resistance Change RAM (RRAM) (metal oxides)
Resistance Change Memory Taxonomy

Example of Electrochemical Memory Implementations

Table I. Summary of reported electrochemical metallization cells employing either Ag or Cu as an active electrode (AE) metal and various electrolytes and counter electrode (CE) metals.

<table>
<thead>
<tr>
<th>Electrolyte</th>
<th>Active electrode (AE) metals</th>
<th>Ag</th>
<th>Cu</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ge₂S₇</td>
<td>W₁₁₋₁₉</td>
<td>W₁₅</td>
<td></td>
</tr>
<tr>
<td>Ge₆Se₇</td>
<td>W₁₁₋₁₆.2₀–₂₇, Pt²⁴ Ni₁₀₂₅₋₂₇</td>
<td>W₇₅</td>
<td></td>
</tr>
<tr>
<td>Ge-Te</td>
<td>TiW²⁸</td>
<td>TaN²⁹</td>
<td></td>
</tr>
<tr>
<td>Ge-Sb-Te</td>
<td>Mo³⁰</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As-S</td>
<td>Au³¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn,Cd₁₋ₓ,S</td>
<td>Pt²²,2₃</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu,S</td>
<td>Pt³⁴,4₀ Ti⁶⁵,7₇</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ta₂O₅</td>
<td>Pt³₆²₄–₄₁ Ru⁴¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SiO₂</td>
<td>Co⁴²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WO₃</td>
<td>W⁴³</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>Pt⁴₇,4₈</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ZrO₂</td>
<td>Au⁴₉</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSQ</td>
<td>Pt⁶⁰,5¹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GdO₃</td>
<td>W⁶²</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a-Si</td>
<td>Poly-Si³²–⁵⁰ Cr⁵⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge₂Se₅/SiOₓ</td>
<td>Pt⁵⁷</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ge₂Se₅/Ta₂O₅</td>
<td>W⁶₈</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu₅S/Cu₂O</td>
<td>Pt⁶⁹</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cu₅S/SiO₂</td>
<td>Pt⁶⁰</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

All arrays utilized 1T:1R (one transistor for device selection and one resistive switching element) architecture. Compiled with information from Chen ᵉ with the addition of data recently reported for Ag/Ge₆Se₇/W cells.¹⁹

Table II. Summary of key performance data reported to date in electrochemical metallization arrays.

<table>
<thead>
<tr>
<th>Material Systems</th>
<th>Cu/Cu,S/Ti</th>
<th>Cu-Te/GdOₓ/W</th>
<th>Ag/Ge₆Seₓ/W</th>
<th>Ag/Ge₆Seₓ or Ge₆Seₓ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>Kaeleyama et al.²⁷</td>
<td>Antani et al.³⁵</td>
<td>Gopalan et al.³⁴</td>
<td>Dietrich et al.⁴⁴</td>
</tr>
<tr>
<td>Array Size Tested</td>
<td>1 kbit</td>
<td>4 kbit</td>
<td>364 kbit, 1 Mbit</td>
<td>2 Mbit</td>
</tr>
<tr>
<td>Technology Node</td>
<td>250 nm</td>
<td>180 nm</td>
<td>180 &amp; 130 nm</td>
<td>90 nm</td>
</tr>
<tr>
<td>SET Condition</td>
<td>1.1 V/5–32 μs</td>
<td>3 V/5 ns/110 μA</td>
<td>1.5 V/250 ns/30 μA</td>
<td>≥0.6 V/50 ns/10 μA</td>
</tr>
<tr>
<td>RESET Condition</td>
<td>1.1 V/5–32 μs</td>
<td>1.7 V/1 ns/125 μA</td>
<td>0.6 V/12 ns/20 μA</td>
<td>≤0.2 V/50 ns/20 μA</td>
</tr>
<tr>
<td>Endurance</td>
<td>10⁻⁸⁻¹⁰²</td>
<td>10²</td>
<td>10²</td>
<td>10⁶</td>
</tr>
<tr>
<td>Retention (measured)</td>
<td>10² s @ 35 mV</td>
<td>100 hours @ 130°C</td>
<td>24 hours @ 110°C</td>
<td>10⁵ s @ 70°C</td>
</tr>
<tr>
<td>Retention (projected)</td>
<td>3 months</td>
<td>10 years</td>
<td>10 years</td>
<td>10 years</td>
</tr>
</tbody>
</table>

Electrolyte and CE materials are indicated in each row. For bilayer electrolytes, AE would be placed to the left of the electrolyte (e.g., Cu/A/B/Pt for a cell with a Cu AE metal and A/B bilayer electrolyte). Information compiled by John R. Jameson, Adesto Technologies Corp. Reprinted with permission from Reference 9. ©2011, IOP Publishing.
What is it Made Of?

Anode

CBRAM uses 25% of all the elements

Electrolyte

CBRAM / CMOS Build uses ~75% of all the elements! More than Moore in action.

Cathode
Operating Principle of a CBRAM Cell

Silver layer
Solid electrolyte
Conductor

Program
$R > 10\text{M\Omega}$

$R_{\text{ON}} \sim k\Omega$

Erase

$R_{\text{OFF}} \sim 10^{10} \Omega$

$R_{\text{ON}} \sim 10^4 \Omega$

Graph showing the relationship between voltage and current, with points indicating the resistance values.
CBRAM cells as quantum point contacts (QPCs)

Physical picture is atomic:

\[ G_0 = \frac{2e^2}{h} = (13k\Omega)^{-1} \]

Not continuum:

Summary of QPC-related device behavior:

“Conductive bridge random access memory (CBRAM) technology”, Jameson & Van Buskirk - in -

Advances in nonvolatile memory and storage technology, ed. Y. Nishi, Woodhead Pub.

Similar observations in other systems:

Non-gap: See paper for 8 refs from 2012/13
Outline/Contents

• Introduction to Adesto Technologies

• Introduction to CBRAM

• CBRAM from Adesto
  – General characteristics
  – High-T retention
  – Radiation tolerance

• Conclusions
CMOS Integration

- Adesto has successfully completed baseline integration flow in a standard CMOS Logic fab
- Adesto’s process integration enables the introduction of CBRAM memory stack into CMOS BEOL without affecting the line
- Over 8000 wafers processed so far without any issue on background CMOS process
1Mb Array Architecture and Diagram

Zone 0

VAN (0)  BL (0)  8-BLs  BL (7)
WL (0)

VAN (127)  BL (0)  BL (7)
WL (255)

127 Sectors

Zone 3

VAN (0)  BL (0)  BL (7)
WL (j)

VAN (127)  BL (0)  BL (7)
Importance of the Fermi wavelength in QPCs

**Metals:**
\[ \lambda_F \sim 1 \text{ Å} \rightarrow 1 \text{ atom} \sim 1 \text{ } G_0 \text{ (13kΩ)} \]

**Semiconductors:**
\[ \lambda_F \gg 1 \text{ Å} \rightarrow 1 \text{ atom} \ll 1 \text{ } G_0 \]

To open first conductance channel \((R \sim 1/G_0)\), need \(d \sim \lambda_F\)

To reach a given \(R_{ON}\), a semi QPC must be wider than a metal QPC

1 atom

13/3 kΩ

3 atoms
CBRAM: Cell Structure and Architecture

- Amorphous alloy containing a semiconductor
- Oxide
- Metal cathode
- BL
- WL
- Anode

- 128kb–1Mb EEPROM-compatible products
- I²C interface
- 1T1R
- 130nm Cu BEOL
Outline/Contents

- Introduction to Adesto Technologies
- Introduction to CBRAM
- CBRAM from Adesto
  - General characteristics
  - High-T retention
  - Radiation tolerance
- Conclusions
CBRAM: Forming

- In general, first write is slower than subsequent writes
- But, high yield still achievable with forming pulse of 10\(\mu\)s/3V
CBRAM: Write Speed

- Write speed depends "exponentially" on voltage
- At a write voltage of 3V, sub-10ns writes are possible
- Typical program uses ~2V/100ns-1us
CBRAM: Erase Speed

- Above a voltage of ~2V, sub-10ns erases are also possible
- Typical erase uses ~1.5V/100ns-1us
CBRAM: Immunity to Read Disturbs

- The exponential dependence of speed on voltage allows read disturbs to be avoided.
- Typical read uses ~0.2V/100ns
Outline/Contents

• Introduction to Adesto Technologies

• Introduction to CBRAM

• CBRAM from Adesto
  – General characteristics
  – High-T retention
  – Radiation tolerance

• Conclusions
The Need for High-T Retention in Emerging Memories

- Operational requirement for some applications (e.g., automotive)
- Other applications (e.g., code storage) utilize wafer-level or package-level programming, followed by solder reflow for board mount
- Low-density demonstrations to prove out new technology

IPC/JEDEC J-STD-020D.1, Fig. 5-1

Reflow T profile

\[ T_P = 260^\circ C, \quad t_P = 30s \]

Worst case: Surface mount of a thin package using Pb-free solder

IPC/JEDEC J-STD-020D.1, Fig. 5-1
CBRAM: Example of Long-term High-T Retention

- Cells are stable at 10x greater R than that of a 1-atom point contact of a typical metal (i.e., \(~1/G_0\)).

- High-T retention of a given R state is insensitive to the operation used to obtain that state.

- Ongoing product-level retention tests at 110°C have shown no fails after more than 8 months.

\[ R_{ON} = 1/G_0 = 13k\Omega \]
CBRAM: Retention through Simulated Solder Reflow

Anneal profile simulating high-T portion of multiple Pb-free solder refows

- Excellent retention is achievable at reflow-like times and temperatures
- Algorithm design is important, even with suitable materials system
Outline/Contents

• Introduction to Adesto Technologies

• Introduction to CBRAM

• CBRAM from Adesto
  – General characteristics
  – High-T retention
  – Radiation tolerance

• Conclusions
Recent News —

Collaboration with Adesto Technologies and Nordion Confirms Gamma Irradiation Tolerance of CBRAM® Non-Volatile Memory

Wednesday, October 16, 2013

*Capability Opens New Market Opportunities to Ultra-Low Power Memory Products*

Sunnyvale, CA, October 16, 2013 -- Adesto Technologies, a memory solutions provider delivering innovative products for code and data storage applications, and Nordion, with global expertise in the design and construction of commercial gamma irradiation systems, today announced the successful completion of gamma irradiation testing of Adesto’s CBRAM non-volatile memory products. The results demonstrated CBRAM’s tolerance for gamma testing with device function and data storage surviving gamma radiation exposure…

“*Gamma irradiation is a proven technique for the sterilization of single use medical devices and other consumer products that require strict microbial decontamination.*” — Emily Craven, Manager of Sterilization Science at Nordion
CBRAM® Gamma Tolerance Study

Study 1: (vs. Conventional Flash)

<table>
<thead>
<tr>
<th>Device</th>
<th>Technology</th>
<th>DUT ID</th>
<th>Gamma Dose (krad Si)</th>
<th>Data Loss (# bit errors)</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>AT25F512B</td>
<td>Floating Gate</td>
<td>1</td>
<td>447</td>
<td>859</td>
<td>FAIL</td>
</tr>
<tr>
<td>AT25F512B</td>
<td>Floating Gate</td>
<td>2</td>
<td>447</td>
<td>6519</td>
<td>FAIL</td>
</tr>
<tr>
<td>AT25F512B</td>
<td>Floating Gate</td>
<td>3</td>
<td>131</td>
<td>955</td>
<td>FAIL</td>
</tr>
<tr>
<td>AT25F512B</td>
<td>Floating Gate</td>
<td>4</td>
<td>131</td>
<td>4</td>
<td>FAIL</td>
</tr>
<tr>
<td>RM24EP128KS</td>
<td>CBRAM</td>
<td>1</td>
<td>447</td>
<td>0</td>
<td>PASS</td>
</tr>
<tr>
<td>RM24EP128KS</td>
<td>CBRAM</td>
<td>2</td>
<td>447</td>
<td>0</td>
<td>PASS</td>
</tr>
<tr>
<td>RM24EP128KS</td>
<td>CBRAM</td>
<td>3</td>
<td>131</td>
<td>0</td>
<td>PASS</td>
</tr>
<tr>
<td>RM24EP128KS</td>
<td>CBRAM</td>
<td>4</td>
<td>131</td>
<td>0</td>
<td>PASS</td>
</tr>
</tbody>
</table>

• Tests performed by ASU

CBRAM had no failure even at twice the normal dose used for Gamma Sterilization

Study 2: (High Dose Gamma)

- Data Retention Test
  - Alternating “1” “0”
  - Checkerboard (CKBD) pattern

- Pre Exposure: Use good parts (Total 80)
  - Write Erase Cycle 10 times
  - Write Alternating Data Patterns of “0” and “1”
  - Pack and Send for Exposure

- Gamma Exposure at Nordion
  - Control 0 rads
  - 1.5 Mrads
  - 2.5 Mrads
  - 5 Mrads

- Post-Exposure Read of Production CKBD

• Tests performed by Nordion – Leading provider of isotopes and radiation therapy services to the medical and health care industry
• Results: CBRAM PASSED Data Retention Test
CBRAM Cell Tolerance to Gamma Radiation – Resistance Distribution

Program State (LRS)  Erase State (HRS)

Sigma Yield

Resistance (Kohm)

50kGy Dose
- After Exposure
- Before Exposure
Summary and Outlook for CBRAM

• Field of emerging memory is diverse and vibrant

• CBRAM has been a leading candidate, and has recently made significant new advancements

• CBRAM has achieved high-T retention by using a combination of materials engineering & a properly designed algorithm
  → Opportunities for apps w/ high-T operation or requiring solder reflow

• Tolerance to gamma radiation has also been achieved
  → Opportunities for medical or aerospace applications