Resistive Switching in Metal-Insulator-Metal Junctions

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I. Introduction
   Random Access Memories

II. Resistive Switching

III. Ferro-Resistive Switching

IV. Summary

V. Multiferroic Tunnel Junction
Charge and Resistance for RAMs

- MRAM
- Flash
- DRAM/SRAM
- FeFET

MIM Junction (Resistive Switch)

Carbon nano tubes

Conductive bridge (Solid State Electrolyte)

Ovonic

Molecular Memory (single molecule)
What is a resistive memory?

Read a Resistance = Resistive Memory

**Examples**

<table>
<thead>
<tr>
<th>Charged Based:</th>
<th>Resistance Based:</th>
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<tr>
<td>DRAM</td>
<td>MRAM</td>
</tr>
<tr>
<td>FeRAM</td>
<td>Flash</td>
</tr>
<tr>
<td>SRAM</td>
<td>FeFET</td>
</tr>
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<td>.....</td>
<td>Ovonic</td>
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<td>....</td>
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</tbody>
</table>
Why resistive storage Elements?
1T1C cell

Bit line

Word line

Transistor

Sense Amplifier

$C_{BL}$

DRAM capacitor
“1” charged Cap.
“0” non charged Cap.

$C_{min} \simeq 30 \text{ fF}$
Planar DRAM Capacitor

$C_{\text{min}} \approx 30 \text{ fF}$

$\text{SiO}_2$ thickness $d$

$Q = C \cdot U; \quad C = \varepsilon_0 \varepsilon A / d$

Decrease capacitor footprint (area $A$) $\Rightarrow$ reduces $C$ ($C_{\text{min}}$ limit)

- Reduce dielectric thickness $d$, tunneling limit (approx. 2nm)
- Increase area by using 3-D structures (keep footprint)
- Use high-$k$ dielectrics (process compatibility with CMOS)
Developments: 3 D capacitors

Siemens / IBM: 1 Gbit, deep trench

Tremendous efforts to stay on the road-map
Challenging technology – more and more expensive and complicated
Different remanent polarization states

⇒ different transient current behavior to an applied voltage pulse

⇒ Integrating the current ⇒ switched charge $Q_S$ and non-switched charge $Q_{NS}$ (distinction between the two logic states)

⇒ Destructive Readout
Scaling and 3D conformal Coverage

<table>
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<tr>
<th>2D planar Pt</th>
<th>Transition from 2D to 3D technology</th>
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<td>Ferroelectric</td>
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Minimum capacitance for sensing: 30 fF
Operation voltage: 1 V

\[ Q = C U \quad n = Q / e \]

\[ 3 \times 10^{-14} \text{C needed for sensing: approx. 20,000 } e^- \]

Planar capacitor:
A = 100 nm x 100 nm
\( P_r = 10 \mu \text{C/cm}^2 \)
\( 10^{-15} \text{ C} \)
\( Q = PA \)

Corresponds to 6000 \( e^- \) not sufficient for data sensing!

3D approach necessary!

Conformal coverage/MOCVD mandatory
Supposed to be implemented in 2007-09 for 100 nm FeRAM node technology
Matrix Architecture: Random Access Memory

Renewed approach: Crossbar arrays
Extremely high scaleable
Go 3-D

First step: Crossbar resistor array
1R cells
< 10 nm feature size

3-dimensional array by stacking:

Although technological difficult – nothing new

Interconnects
Second step: New Nanoelectronic Architectures


Approach:

Activate independently at the cross points different devices as: (switchable) resistors, diodes or transistors

Create your own Computer after the fabrication process.

Beyond conventional memory architecture! Field programmable arrays (FPGA)
The Resistive Memory Approach

Bi-stable (or multi-stable) resistors

Current

Voltage

$V_{threshold} = V_{th}$

$V_{read} < V_{th}$
...more specific

Read a Resistance = Resistive Memory

Magnetic Tunnel Junctions

Indirect type:

No structural changes in the transport region between on and off state

Direct type:

Structural changes (e.g. Phase Change)
Two Parties:

**Homogenous folks:**
Those who believe the effect is a volume or an interface effect across the entire dielectric and/or interface.

**Filament (network) folks:**
Those who believe the effect is caused by filaments which are strongly localized in an inactive surrounding.
Overview Resistive Switches (Effects)

Homogeneous

? How homogeneous is the current transport - Filaments?

Local

?Is a formation process important?

?Which role play the interfaces?

Redox

➢Red$^\cdot$ ↔ Ox + $e^\cdot$

➢Voltammogram

?Is the switching effect a pure electronic or ionic or a superposition?

?Which kind of current transport is essential for $R_H$ and $R_L$?
Not a surprise:

Number of models $\geq$ Number of groups in the field

Device Examples…
Examples: Organics

Rose Bengal (70nm) or AlOx (5nm)


B. Lüssem et al., submitted to J. Appl. Phys.

Even without the Polymer, the I-V curves look very similar!
Organics

Very different organics show very similar I-V curves!

Hewlett-Packard

Conductive bridges (filaments)!
Oxidation and reduction of the Ti interface layer results in a bi-stable resistance.
Electron Trap Model: An Example


Effect: Charging (decharging) by electrons in the (top) and (bottom) barriers → Change of the conductance of the adjacent organics.

Examples: Inorganics

Material: *Transition metal oxide* $\text{Nb}_2\text{O}_5$ (or sub-oxides)

Based on: Nb-Nb$_2$O$_5$-Bi

D. P. Oxley, *Electrocomp. Sci. and Techn.* 3, 217 (1977) and references therein
Inorganics

A. Beck et al., APL 77, 139 (2000)
IBM, IBM Zürich

IBM Zürich

SrRuO$_3$/SrZrO$_3$:Cr0.2%/Pt
Resistive switching in SrTiO$_3$

Switching the electrical resistance of individual dislocations in single-crystalline SrTiO$_3$
K. Szot, W. Speier, G. Bihlmayer and R. Waser
Nature Materials 2006
Ferro-Resistive Switch

Material: \( \text{PbZr}_x\text{Ti}_{1-x}\text{O}_3 \) (ferroelectric-semiconductor)

Based on: Pt-PZT-Nb:SrTiO3

Ferroresistive Switching

Self-consistent steady state solution: Drift-Diffusion transport and the Poisson equation.

1-D Simulation of a Novel Nonvolatile Resistive Random Access Memory Device
R. Meyer and H. Kohlstedt
to be published in IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control

K. Gotoh et al.,
FerroResistive-RAM

\[ P_s \]

\[ \rho(x) \]

\[ E(x) \]

\[ e\phi(x) \]

potential barrier
FRRAM

\[ \rho(x) \]

\[ E(x) \]

\[ e\varphi(x) \]

potential well
The diagram illustrates the relationship between current density and voltage for a semiconductor device. The ordinate represents current density in units of $10^5 \times A/cm^2$, while the abscissa represents voltage in Volts (V). An inset graph shows the donor content as a function of the carrier density ($10^{17} - 10^{20}$). The device's doping concentration ($N_D = 10^{19} \text{cm}^{-3}$) is indicated at the bottom right corner.
How to distinguish a ferroelectric origin from a non-ferroelectric one?

Experimental result

Numerical model

Although the curves look similar – its not a proof!

R. Meyer

Current [mA]

Voltage [V]

-2,0 -1,0 0,0 1,0 2,0

Thickness: 6.4 nm

Area: 3 µm²

Pt

PZT (20/80)

SrRuO₃

SrTiO₃

January, 2003

N₀ = 10¹⁹ cm⁻³
Resistive Switching and Ferroelectric Origin
( across $T_c$ )

Switching ($T < T_c$)  no switching ($T > T_c$)

but in (ultra) thin films:

- $T_c$ not known
- broad phase transition
- $T_c$ modified by external field

Interpretation difficult
Resistive Switching and Ferroelectric Origin

Area: 0.04 \( \mu \text{m}^2 \)
Simultaneous Measurement of different FE-Properties

A. Petraru et al., to be published in Appl. Phys. A

To measure $d_{33}$, $C$ and $l$ (resistive) vs. bias voltage simultaneously
Resistive Switching and Ferroelectricity

$d_{33}$ vs. Bias

**Graph Details:**
- **$d_{33}$ (a.u.)** vs. **$U$ (V)**
- **Y-axis range:** $-8 \times 10^{-4}$ to $8 \times 10^{-3}$
- **X-axis range:** $-1.0$ to $1.0$

**Graph Annotation:**
- **Arrow indication:** Reversal of $d_{33}$ direction

**Stacked Layer Illustration:**
- **Pt**
- **PZT (20/80)**
- **SrRuO$_3$**
- **SrTiO$_3$**

**Materials Specifications:**
- **Thickness:** 30 nm
- **Area:** 3 µm$^2$
Resistive Switching and Ferroelectricity

$d_{33}, C$ vs. Bias

$C (pF)$

$-1.0$  $-0.8$  $-0.6$  $-0.4$  $-0.2$  $0.0$  $0.2$  $0.4$  $0.6$  $0.8$  $1.0$

$U (V)$

$-8 \times 10^{-4}$  $-6 \times 10^{-4}$  $-4 \times 10^{-4}$  $-2 \times 10^{-4}$  $0$  $2 \times 10^{-4}$  $4 \times 10^{-4}$  $6 \times 10^{-4}$  $8 \times 10^{-4}$  $1 \times 10^{-3}$

$Pt$

$PZT (20/80)$

$SrRuO_3$

$SrTiO_3$
Resistive Switching and Ferroelectricity

\[ d_{33}, C, I_{\text{res.}} \text{ vs. Bias} \]

- \( d_{33} \) (a.u.)
- \( I \) (\( \mu \)A)
- \( C \) (pF)

- Pt
- PZT (20/80)
- SrRuO\(_3\)
- SrTiO\(_3\)

- \( V_c = -0.5V \)
- \( V_c = 0.6V \)

U (V)
Increase Bias Voltage…

AFM

PZT (20/80)

SrRuO$_3$

SrTiO$_3$

$\begin{align*}
\text{U (V)} \\
-1.5 & -1.2 & -0.9 & -0.6 & -0.3 & 0.0 & 0.3 & 0.6 & 0.9 & 1.2 & 1.5 \\
\end{align*}$

$\begin{align*}
\text{l (mA)} \\
-4 & -3 & -2 & -1 & 0 & 1 & 2 & 3 & 4 & 5 \\
\end{align*}$
Resistive Switching and Ferroelectricity

- Resistive Switching
  - Pt Resistive Switching
  - SrRuO$_3$
  - PZT (20/80)

- Ferroelectric Switching
  - V$_c$ = -0.5V
  - V$_c$ = 0.6V

Heat!

U (V)

V$_r$

Ferroelectric Switching

I (mA)
Resistive Switching and Ferroelectricity

Current density high enough for heat generation?

Estimation: \( I = 10 \, \mu A, \ r_{\text{tip}} = 5 \, \text{nm} \)

\[
J = \frac{I}{A}
\]

\[
J = 1.5 \times 10^7 \, \text{A/cm}^2
\]

If current > 10 \( \mu A \),
heating affects cantilever deflection
When the current through the tip exceeds 15 µA, the piezoresponse is affected via thermal effects!
Resistive Switching caused by Ferroelectricity?

![Diagram showing a current-voltage graph with a log-log scale. The graph plots resistance (\(\rho\)) against area (\(A\)). There are two distinct regimes: high resistance (\(R_{high}\)) and low resistance (\(R_{low}\)). The material layers include Pt, PZT, SrRuO\(_3\), and SrTiO\(_3\). The thickness of the PZT layer is 30 nm.](image)

\[
\begin{align*}
\rho_{high, low} (\Omega cm) & \\
\text{Area (cm}^2\text{)} & \\
10^{-6} & 1 \times 10^{-5} & 1 \times 10^{-4}
\end{align*}
\]
Resistive Switching: Filament Model

K. Szot, FZ Jülich

Schematic cross-section

30nm

Ferroelectric PbZr\textsubscript{0.20}Ti\textsubscript{0.80}O\textsubscript{3}

SrRuO\textsubscript{3}

SrTiO\textsubscript{3}

Top view

Breakdown points (if resistive switching appears)


K. Szot et al. Switching the electrical resistance of individual dislocations in single-crystalline SrTiO\textsubscript{3}, to be published in Nature Materials
Resistive Switching: Filament Model

G. Dearnaley, A. M. Stoneham and D. V. Morgan

G. Dearnaley,
Crossbar Arrays:
Resistive switches for crossbar arrays,
Many materials show resistive switching, no theoretical understanding, devices performance not yet sufficient for applications,
Aim: feature size < 10 nm, if possible single molecules
Fabrication: Nano-imprint/Self Assembly

3 Dimensional circuits

Field Programmable Arrays

Cognitive Memories
Overview Resistive Switches (Materials)

Insulator/Semiconductor/amorphous/crystalline/poly-crystalline

Electronic

Oxides:

Mixed conductor (Ionic/Electronic)

Ferroelectric

Complex Oxides:

Mixed conductor (Ionic/Electronic)

Ferroelectric

Chalcogenides:

Mixed Conductor (Ionic/Electronic)

Phase Change

Inorganic

Organic

Ferroelectric

Electronic

Mixed Conductor (Ionic/Electronic)

Single Molecule

Carbon Nanotubes
Summary

- Crossbar arrays are attractive for high-density memories
- Resistive switching is observed in many different materials
- Up to now no clear theoretical background
- The resistive switching is often a result of conductive bridges

- Ferroresistive material show resistive switching
  The origin of the effect can be analyzed by simultaneous measurement of different ferroelectric properties
### Research Center Juelich:
- A. Petraru (Post Doc)
- A. Kaiser (Student)
- U. Poppe, J. Schubert, C. Buchal
- M. Indlekofer
- R. Meyer
- H. Schroeder
- C. Jia
- R. Waser

### External Collaborations:
- N. A. Pertsev – Landau Theory
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- D. Schlom – Complex Oxides MBE
  - *Penn State University, Depart. of Material Science, USA*
- Ph. Ghosez – Ab-initio theory on ferroelectrics
  - *University of Liège, Belgium*
- V. Nagarajan- Ultra thin ferroelectric films
  - *University of South Wales, Sydney*
- R. Ramesh
  - *University of Berkeley, Depart. of Material Sci., USA*
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University of Aachen (RWTH)
Research Center Jülich
„Displacive and Conductive Phenomena in Ferroelectric Thin Films:
Scaling effects and switching properties“. 
## References:

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<thead>
<tr>
<th>Non-Volatile Memories: Overviews/Books</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>B. Prince, Emerging Memories – Technology Trends, (Kluwer Academic Pub. 2002).</td>
<td>Explains only the rough principles: Many figures are of bad quality</td>
</tr>
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</table>