Memristive behavior in magnetoelectric devices

Concepts and Prospects

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Magnetoelectric effect

Intrinsic ME effect: weak coupling, cannot be used @ room temperature

Artificial ME effect, eg mechanical stress through magnetostriction

Practical applications can be considered
Magnetoresistance to read information

Now we know how to read and write
MELRAM : Bistable magnetolectric cell

Concept of MELRAM

Magnetoelectric memory, Extension PCT WO/2011/158208

Tensile stress along X (σ > 0):

Compressive stress along X (σ < 0):

Key advantage:
Energy consumption

Switching energy ~ 10 aJ


Electrical behavior dynamics

Bistability means impossible to control magnetization step by step

Sacrificing bistability for continuous angular magnetization control

Can’t have both hysteresis and continuous resistance variation

Let’s look at devices with a domain walls
New device

Very same concept, but with a two-domain configuration

\[
\sigma > 0 \quad \sigma < 0
\]

Chanthbouala et al. Nature Physics, 2011

DW motion… and ejection

I(t)
Variable section

Results: DW motion with intermediate states

Stays in any given state only if stress is maintained because of perfectly smooth profile

Hysteresis is almost surely a numerical artifact. Anyway, experimentally there will be sources of irreversibility.
Understanding the underlying physics

We consider a one-dimensional ferromagnet with two domains. Let’s write the total energy of our system:

\[ E_{tot} = \iiint_V \left( e_{uni} + e_{Zeeman} + e_{exch} + e_{stress} \right) dV \]

\[ E_{tot} = \int_{-\frac{L}{2}}^{\frac{L}{2}} S(x) e_{tot}(x) dx \]

S is the section, various profiles can be tested.

We can either:
- solve for \( \theta(x) \) minimizing the energy
- Extract DW position from equilibrium criteria

Two simple, complementary models.
1D model results

Solving for $\theta$

Equilibrium condition gives final DW position

Ideally, $x_p$ gives resulting resistance

$\Rightarrow$ No hysteresis here
Magnetoelectric memristor

• Voltage controlled memristor (sub 1V)
• Step by step operation
• Significant maximum conductance contrast (80-90%)
• Unequivocal operation given sign of V
• Energy efficient
  MELRAM switching energy $\sim 10^3 \, kT < 10 \, aJ$
• ~ compatible with crossbar geometries

Key advantage is energy consumption
Appropriate for power-aware computing
Experimental realization

What has been done:
- Successful lift-off for electrodes on PMN-PT
- 5µm-wide piezo stud, w/ Focused Ion Beam

Next:
Plasma etching instead of FIB to scale the process

In parallel:
- Further geometrical design optimization
- Finding best magnetic parameters compromise
- Electronic lithography on plain PMN-PT

- Plan to build a magneto-optical microscope to look at magnetic domains
The idea is to move a domain wall with mechanical stress.