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MESOSCOPIC MODELING OF FERROIC AND MULTIFERROIC MATERIALS

Avadh Saxena (Los Alamos National Lab)

1. Strain: **order parameter** (symmetry determined).
2. Landau **free energy**; gradient energy.
3. Domains, microstructure and **elastic compatibility**.
4. Coupling of strain to **polarization/magnetization**; multiferroics.
5. Disorder: spin glass, relaxors, **strain glass**.
6. **Bioferroics**: Ferroic phenomena in biology.

Collaborators: **T. Lookman, A. Planes, T. Castan, K. Otsuka, X. Ren.**

Three Pillars of Functional Materials/Devices

CHARGE

SPIN

LATTICE

Tholos Temple at Delphi, Greece, 300 BC

FERROIC MATERIALS

Ferroics: Family of materials exhibiting one or more **functional characteristics** such as magnetization (in ferromagnetic materials), polarization (in ferroelectric materials), strain (in ferroelastic materials), which **occur at a** (often first-order) **phase transition**.

Features:

1. **DOMAINS** occur at the **transition**.
2. Functional properties can be **SWITCHED** by an external **conjugate field**.
3. They show **HYSTERESIS** (and thus **spontaneous order** at zero field).
4. They can be **utilized** as **SMART** materials.

Four Primary Ferroics: Symmetry

<div>time \ space</div>	invariant	change
invariant	ferroelastic	ferroelectric
change	ferromagnetic	ferrotoroidic

Ferroics with vector order parameter

<div>Time</div> <div>Space</div>	invariant	change
	<div>ferrotoroidic [E]</div>	<div>ferroelectric</div>
change	<div>ferromagnetic</div>	<div>ferrotoroidic [M]</div>

Dipolar vortices

S. Prosandeev et al. (2008)

DIPOLE MOMENT (vector)

ELECTRIC (polar)

$$\sim 1/r^3$$

MAGNETIC (axial)

$$\sim 1/r^3$$

TOROIDAL (axio-polar)

$$\sim 1/r^5$$

HYPERTOROIDAL MOMENT

ELECTRIC

Double vortices

MAGNETIC

S. Prosandeev and L. Bellaiche
J. Mater. Sci. 44, 5235 (2009).

ELASTIC DIPOLE MOMENT (polar tensor)

DEVIATION FROM SPHERICITY ($\sim 1/r^5$)

FERROIC PROPERTY QUADRANGLE

FERROICS	Property	Precursor	Glass	Caloric
Ferromagnetic	M	Magnetic tweed	Spin glass	Magnetocaloric
Ferroelectric	P	Polar tweed	Polar glass	Electrocaloric
Ferroelastic	e	Tweed	Strain glass	Elastocaloric
Ferrotoroidic	T	Toroidic tweed	Toroidic glass	Toroidocaloric

SYMMETRY, FREE ENERGY MICROSTRUCTURE

Elements of Landau Theory

Lev Davidovich
Landau 1908-1968

- **Symmetry**-based treatment
- Introduces formally the **Order Parameter**.
- Starting point: in the vicinity of the phase transition the **free energy** can be expanded in powers of the Order Parameter.
- The expansion includes only terms which are allowed by **symmetry**.

LANDAU THEORY

$$e_1 = \varepsilon_{xx} + \varepsilon_{yy}$$

$$e_2 = \varepsilon_{xy}$$

$$e_3 = \varepsilon_{xx} - \varepsilon_{yy}$$

1. Distortion:

$$\Delta\rho(r) = \rho_0(r) - \rho(r)$$

2. Strain:

$$\Delta\rho(r) = \sum C_{ij} \varepsilon_{ij}$$

$$= \eta_1 e_1 + \eta_2 e_2 + \eta_3 e_3$$

3. Free energy:

$$F[\delta\rho] \rightarrow F[e_1, e_2, e_3] \xrightarrow{\text{OP}} F[e_3]$$

4. Truncation:

$$F[e_3] = a(P, T) e_3^2 + b e_3^3 + c e_3^4$$

$$F[e_3] = a(P, T) e_3^2 + b e_3^4 + c e_3^6$$

$$F[e_3] = a(P, T) e_3^2 + c e_3^4$$

Ockham's
Razor !

Relationship with Theory and Experiments

Microstructure for Structural Transitions

Order Parameters

Functionalities ε, P, M, ψ

Landau, 1937

+

Spatial variations

Ginzburg, 1955

➡ **Free Energy** : $F(\varepsilon, P, M, \psi : \nabla \varepsilon, \nabla \psi ..)$

Adhemar Jean Claude Barre de Saint-Venant

1797 - 1886

Strain: lattice as an elastic template

Saint Venant Compatibility, 1864

Lookman et al, PRB, 2003; 2004

$$\nabla \times (\nabla \times \vec{\epsilon})^T = 0$$

Strains not unique

$$\epsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Constraint → anisotropic long-range force

Lookman, Fellows

Coherent strain matching of parent and variants :

Finite
width

Finite
plate

misfit $\rightarrow$ decaying strain fields

Strains & Compatibility

$$\varepsilon_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$$

Elastic compatibility:

$$\nabla^2 \varepsilon_1 - \left(\frac{\partial^2}{\partial x^2} - \frac{\partial^2}{\partial y^2} \right) \varepsilon_2 - \sqrt{8} \frac{\partial^2}{\partial x \partial y} \varepsilon_3 = 0$$

(a) coherent

(b) incoherent

Elastic energy:

$$= A_1 \varepsilon_1^2 + A_2 \varepsilon_2^2 + A_3 \varepsilon_3^2$$

Free energy for

$$F = \int d\vec{r} [F_{elas} + F_{struct} + F_{load}]$$

$$F_{struct}(\epsilon_2) = \frac{a(T - T_0)}{2} \epsilon_2^2 - \frac{B}{4} \epsilon_2^4 + \frac{C}{6} \epsilon_2^6 + \frac{g}{2} |\nabla \epsilon_2|^2$$

Free energy for

$$F = \int d\vec{r} [F_{elas} + F_{struct} + F_{load}]$$

$$F_{struct}(\epsilon_2) = \frac{a(T - T_0)}{2} \epsilon_2^2 - \frac{B}{4} \epsilon_2^4 + \frac{C}{6} \epsilon_2^6 + \frac{g}{2} |\nabla \epsilon_2|^2$$

Uniaxial External Stress:

$$F_{load} = -\sigma \epsilon_{xx} = -\frac{\sigma}{\sqrt{2}} (\epsilon_1 + \epsilon_2)$$

ANISOTROPIC LONG-RANGE INTERACTION

Elastic energy

$$F_{elast} = A_1 \epsilon_1^2 + A_3 \epsilon_3^2 + A_2 \epsilon_2^2$$

compatibility

$$\sum_{r,r'} \epsilon_2(r) U(|r-r'|) \epsilon_2(r')$$

$$U(r) \sim \frac{\cos 4\theta}{r^2}$$

$$U(k) = \frac{k_x^2 - k_y^2}{k^4 + \frac{A_1}{A_3} k_x^2 k_y^2}$$

Shenoy et .al. PRB (1999), Lookman et al. PRB (2003)

Defect induced microstructure

• tetragonal defect within

• initial state with seeds within

Lookman et al. 2003

Free energy: Triangle

$$e_2 = \frac{\varepsilon_{xx} - \varepsilon_{yy}}{\sqrt{2}}, e_3 = \varepsilon_{xy}$$

$$F_{struct}(e_2, e_3) = \mathbf{A}_0(T - T_0)(e_2 + e_3)^2 + \mathbf{B}e_3(e_3^2 - 3e_2^2) + \mathbf{C}(e_2 + e_3)^4$$

$$+ \frac{\mathbf{g}}{2}(|\nabla e_2|^2 + |\nabla e_3|^2)$$

Domain wall energy

$$+ \frac{A_1}{2}e_1^2$$

Area change

Lead Orthovanadate:

Triangular

Centered Rectangle

soft

hard

Underdamped

OP

Non-OP

$\text{Pb}(\text{VO}_4)_3$

Lookman et al. Phys. Rev. B, **67**, 024114 (2003)

•Example: Cubic to Tetragonal

Figure 4.4: The three variants of martensite in a cubic to tetragonal transformation.

Order parameter

$$\left(e_2 = \frac{\epsilon_{xx} - \epsilon_{yy}}{\sqrt{2}}, e_3 = \frac{\epsilon_{xx} + \epsilon_{yy} - 2\epsilon_{zz}}{\sqrt{6}} \right)$$

Barsch & Krumhansl, 84, Falk, 83

AUSTENITE

TWEED

$T_0 = 2.68 \text{ K}$

(TWINNED)
MARTENSITE

Sugiyama
(1985)

SYMMETRY ADAPTED STRAINS FOR CUBIC SYSTEM

$$e_1 = \varepsilon_{xx} + \varepsilon_{yy} + \varepsilon_{zz}$$

e_1

e_2, e_3

e_4, e_5, e_6

3[111]

e_1

$$-\frac{1}{2}e_2 + \frac{\sqrt{3}}{2}e_3, -\frac{\sqrt{3}}{2}e_2 - \frac{1}{2}e_3$$

e_6, e_4, e_5

4[001]

e_1

$-e_2, e_3$

$-e_4, e_6, -e_5$

2[110]

e_1

$-e_2, e_3$

$e_4, -e_6, -e_5$

Free energy for Cubic $\longrightarrow$ Tetragonal transition

Order Parameter

$$\left(e_2 = \frac{\epsilon_{xx} - \epsilon_{yy}}{\sqrt{2}}, e_3 = \frac{\epsilon_{xx} + \epsilon_{yy} - 2\epsilon_{zz}}{\sqrt{6}} \right)$$

$$e_1 = \frac{\epsilon_{xx} + \epsilon_{yy} + \epsilon_{zz}}{\sqrt{3}}$$

$$\begin{aligned}
 F(e_2, e_3) = & \mathbf{A}_0(T - T_0)(e_2^2 + e_3^2) + \mathbf{B}e_3(e_3^2 - 3e_2^2) + \mathbf{C}(e_2^2 + e_3^2)^2 \\
 & + \mathbf{E}e_1(e_2^2 + e_3^2) \quad \leftarrow \text{Transformation} \\
 & + \frac{A_B}{2}e_1^2 + \frac{A_S}{2}(\epsilon_{xy}^2 + \epsilon_{xz}^2 + \epsilon_{yz}^2) \quad \leftarrow \text{Volume change} \\
 & + \frac{\mathbf{g}}{2}(|\nabla e_2|^2 + |\nabla e_3|^2) \quad \leftarrow \text{Nonlocal strain inhomogeneity}
 \end{aligned}$$

Simulated 3D microstructure for a model Cubic-Tetragonal Transformation

Figure 4.4: The three variants of martensite in a cubic to tetragonal transformation.

$$e_2 = \varepsilon_{xx} - \varepsilon_{yy}$$

With Volume Change

FePd

DYNAMICS

EQUATION OF MOTION FOR DISPLACEMENT FIELDS

$$\rho \ddot{\vec{u}} = \vec{\nabla} \cdot \vec{\sigma}_{elastic} + \vec{\nabla} \cdot \vec{\sigma}_{dissipative}$$

$$\sigma_{ij}^{elastic} = \frac{\delta F}{\delta \epsilon_{ij}}$$

$$\sigma_{ij}^{dissipative} = \frac{\delta R}{\delta \dot{\epsilon}_{ij}}$$

Rayleigh Dissipation: $R = \int d\vec{r} A'_{ijkl} \dot{\epsilon}_{ij} \dot{\epsilon}_{kl}$

$$\frac{g}{A_o \delta^2} \nabla^2 \epsilon \quad \delta \sim 1nm$$

$$\ddot{\vec{u}} = \vec{\nabla} \cdot \vec{\sigma}_{elastic} + \xi \vec{\nabla} \cdot \dot{\epsilon}$$

$$\xi = \frac{A'_1}{A_o} \sqrt{\frac{A_o}{\rho \delta^2}} \quad .015 Nsm^{-2}$$

$$t \sim 10^{-12} s$$

STRAIN LOADING SIMULATIONS

UNIAXIAL TENSILE LOADING FOR FePd

$$\begin{aligned}\epsilon_{xx} &= \epsilon_{xx} + \epsilon_{applied} \\ \epsilon_{applied} &= \dot{\gamma} t \\ \dot{\gamma} &\longrightarrow \text{strain rate}\end{aligned}\quad \sigma_{xx} = \left\langle \frac{\delta F}{\delta \epsilon_{xx}} \right\rangle$$

↑
average stress

R. Ahluwalia, T. Lookman, A. Saxena, Acta Mater. 54, 2109 (2006).

MICROSTRUCTURE EVOLUTION: FePd

STRESS-STRAIN CURVE: Uniaxial Loading

(shape memory regime: FePd)

STRESS-STRAIN CURVES: Three different Strain Rates

DISORDER: FERROIC GLASS

What is ergodicity?

----- Anything that can happen will happen!

➤ An ergodic system can visit all its possible states within experimental time.

NON-ERGODICITY OF GLASS

Short time relaxation
(Ergodicity)

Unfrozen glass

Glass
transition

Frozen glass

Long time relaxation
(Non-ergodicity)

Not all thermodynamically equivalent states
are accessible in experimental time
→ history dependence of static properties

Fig. 8.2 Sketch of the multi-valley landscape as a function of temperature for a spin glass.

THREE STATES IN CONDENSED MATTER

ZFC/FC of strain glass—striking similarity among the three different kinds of glass

Y. Wang et al., Phys. Rev. B 76, 132201 (2007)

Local strain ordering in strain glass

X. Ren et al. (2008): $\text{Ni}_x\text{Ti}_{1-x}$

Nanodomains in **PLZT** & **PMN** relaxors

Appl. Phys. Lett. **86**, 202907 (2005)

V.V. Shvartsman et al.

Local strain ordering in strain glass

PRL **112**, 025701 (2014)

PHYSICAL REVIEW LETTERS

week ending
17 JANUARY 2014

Y. Zhou et al., $\text{Ti}_{50}\text{Pd}_{41}\text{Cr}_9$

Simulations of strain glass: anisotropy

Elastic anisotropy: $A = 2C_{44}/(C_{11}-C_{22})$

P. Lloveras et al., Phys. Rev. Lett. 100, 165707 (2008)

MRS Bulletin p.838 (Nov. 2009)

Criticality and the piezoelectric response of ferroelectrics

W. Liu and X. Ren, Phys. Rev. Lett. **103**, 257602 (2009)

Extended 2D Ginzburg-Landau model for BaTiO₃

$$G = G_{GL} + G_{em} + G_{es}$$

- **Ginzburg-Landau free energy** (Li *et al.* J. Appl. Phys. **98**, 064101 (2005))

$$G_{GL} = \frac{1}{2} a_2 (T - T_C) P^2 + \frac{1}{4} a_4(\vec{n}) P^4 + \frac{1}{6} a_6(\vec{n}) P^6 + \frac{1}{8} a_8(\vec{n}) P^8 + G_G(\nabla \vec{P}) - \vec{P} \cdot \vec{E}_{ext}$$

- **Electromechanical energy (Elastic energy + Polarization-Strain coupling)**

$$G_{em} = \frac{1}{2} A_1 e_1^2 + \frac{1}{2} A_2 e_2^2 + \frac{1}{2} A_3 e_3^2 + \alpha e_1 (P_x^2 + P_y^2) + \beta e_2 (P_x^2 - P_y^2) + \gamma e_3 P_x P_y - e_1 \sigma_1$$

Random variable
(quenched disorder)

- **Electrostatic energy**

$$G_{es} = -\frac{1}{2} \vec{P} \cdot \vec{E} = \frac{\epsilon_0}{2} E^2 \quad \longrightarrow \quad \int G_{es} d\vec{r} = \frac{1}{2\epsilon_0} \int \frac{d\vec{k}}{(2\pi)^2} \frac{|\vec{k} \cdot \vec{P}|^2}{k^2}$$

Piezoelectric response near the C-T transition of [001] poled BaTiO₃

Clean limit: No disorder

- Divergence of d_{33} at the critical point
- $\vec{P} \parallel \vec{E}$
- Soft potential with respect to the modulus of $\vec{P}$

No polarization rotation!

Piezoelectric response near the C-T transition of [001] poled BaTiO₃

Small disorder:

$$\sqrt{\langle \sigma_1^2 \rangle} = 2.0 \times 10^9 \text{ N/m}^2$$

- Smaller critical electric field (with respect to the clean limit)
- Divergence of d_{33} at the critical point
- **No broadening of the region where d_{33} is large**

Piezoelectric response near the C-T transition of [001] poled BaTiO₃

Large disorder:

$$\sqrt{\langle \sigma_1^2 \rangle} = 4.5 \times 10^9 \text{ N/m}^2$$

- Existence of a critical point
- d_{33} is maximum near the critical point
- d_{33} does not diverge at the critical point

RELAXOR!

MULTIFERROIC TRANSITIONS

Hexagonal RMnO_3 : R=Ho, Er, Tm, Yb, Lu, Y, Sc

Th. Lonkai et al., JAP 93, 8191 (2003): **Weak interlayer coupling**

I. Munawar, S.S. Curnoe, J. Phys. Cond. Matt. 18, 9575 (2006)

Magnetic Structure and SHG Selection Rules

At least 8 different triangular in-plane spin structures with different magnetic symmetries and different selection rules for SHG

α structures: SHG for $k||z$ **allowed**

$$\alpha_x (\varphi = 0^\circ): \quad \chi_{xxx} = 0, \quad \chi_{yyy} \neq 0$$

$$\alpha_y (\varphi = 90^\circ): \quad \chi_{xxx} \neq 0, \quad \chi_{yyy} = 0$$

$$\alpha_p (\varphi = 0-90^\circ): \quad \chi_{xxx} \propto \sin \varphi, \quad \chi_{yyy} \propto \cos \varphi$$

β structures: SHG for $k||z$ **not allowed**

$$\beta_x, \beta_y, \beta_p: \quad \chi_{xxx} = 0, \quad \chi_{yyy} = 0$$

Determine β structure from α - β transition

$$\alpha_x \rightarrow \beta_y: \quad \chi_{xxx} = 0, \quad \chi_{yyy} \propto \cos \varphi$$

$$\alpha_y \rightarrow \beta_x: \quad \chi_{xxx} \propto \sin \varphi, \quad \chi_{yyy} = 0$$

**Contrary to diffraction techniques:
 α and β models clearly distinguishable!**

SH spectrum and Magnetic Symmetry

The magnetic symmetry, **not** the R ion, determines the SH spectrum of $RMnO_3$

Free Energy for a 2D Multiferroic Transition

$$F(M,P,e) =$$

$$\begin{aligned} & a_1(M_1^2+M_2^2)+b_1(M_1^2+M_2^2)^2+c_1(M_1^4+M_2^4) \\ & +a_2(P_1^2+P_2^2)+b_2(P_1^2+P_2^2)^2+c_2(P_1^4+P_2^4) \\ & +a_3(e_2^2+e_3^2)+b_3(e_2^3-3e_2e_3^2)+c_3(e_2^2+e_3^2)^2 \end{aligned}$$

$$\begin{aligned} & +A[e_2(P_1^2-P_2^2)+e_3P_1P_2] \\ & +B[e_2(M_1^2-M_2^2)+e_3M_1M_2] \\ & +C[(P_1^2+P_2^2)(M_1^2+M_2^2)] \end{aligned}$$

+ gradient terms

Gradient couplings: domains & vortices

$$F_G = M^2(\nabla \cdot P) + M \cdot [(M \cdot \nabla)P]$$

$$+ P \cdot [M(\nabla \cdot M) + P \cdot [M \times (\nabla \times M)]]$$

$$+ \varepsilon(\nabla \cdot M)^2 + \varepsilon(\nabla \times M)^2$$

$$+ \varepsilon(\nabla \cdot P) + P \cdot (\nabla \varepsilon) + \varepsilon(\nabla \times P)^2$$

Microstructure simulations underway

DISLOCATIONS IN MAGNETIC CRYSTALS

EDGE: AFM spin ordering

SCREW: spiral spin distribution

BIOFERROICS

Biomagnetism

Bioelectricity

Bioelastic

Bitoroidic

BIOFERROICS

Biomagnetism

Bioelectricity

Bioelastic

Bitoroidic

Conclusions

- Ferroelastics: **strain** as the order parameter.
- Microstructure: **elastic compatibility**.
- **Magnetic** shape memory: coupling to strain.
- **Ferroics**: Ferrotoroidicity; fourth primary ferroic.
- Various **dipole**, and long-range interactions.
- **Ubiquity** of glassy behavior (disorder): **strain glass**.
- Ferroic phenomena in **biological** systems.

Nanodomains in **PMN relaxor**

DISPLACIVE MARTENSITIC TRANSFORMATIONS

- First order, **solid-solid structural phase transformation**.
Ex. Cubic (austenite) to Tetragonal (martensite) transition in FePd alloys.

Figure 4.4: The three variants of martensite in a cubic to tetragonal transformation.

Parameters from experiments

Lattice parameters

$$\eta_1 = \frac{a_t - a_o}{a_o} = .0176 \quad \eta_3 = \frac{a_c - a_o}{a_o} = -.0335$$

$$\varepsilon_{xx} = \varepsilon_{yy}$$

$$\varepsilon_{zz}$$

$$e_2 = 0; e_3 = \varepsilon_0 = \frac{2(\eta_1 - \eta_3)}{\sqrt{6}}; e_1 = \frac{2\eta_1 + \eta_3}{\sqrt{3}}$$

$$\frac{A_B}{2} e_1^2 + \mathbf{E} e_1 (e_2^2 + e_3^2) = 0 \rightarrow e_1 = -\frac{\mathbf{E}}{A_B} (e_2^2 + e_3^2)$$

Elastic constant

$$A_o = \frac{\mathbf{B}^2}{C'} \quad \varepsilon_0 = \frac{\mathbf{B}}{2C'}$$

$$\sigma = C - \frac{\mathbf{E}^2}{A_B}$$

- Phonon dispersion

$$\left[\frac{\omega}{\sin(\pi k / 2)} \right]^2 = \mathbf{A}_0(T - T_c) + \mathbf{g} \sin^2(\pi k / 2)$$

Sato et al (1982)

ϵ_{xx}

ϵ_{yy}

ϵ_{zz}

260K

230K

A **B** **C** **D** **E**

ε_{xx}

ε_{yy}

ε_{zz}

$\times 10^{-3}$

$\times 10^{-3}$

Ferroic: “crystal with two or more distinct orientation states (“domains”) and switching between them”

(Aizu, 1969; Wadhawan, *Intro. to ferroic materials*, 2000)

ferroelectric, ferromagnetic, **ferroelastic**, ferrotoroidal, ferrogyrotropy, ..

Symmetry breaking: Para $\rightarrow$ Ferroic

Ferroic: “crystal with two or more distinct orientation states and switching between them by external fields”

(Aizu, 69)

Multiferroic: two or more coexisting **ferroic** properties in the same phase

Ferromagnetic

Ferroelectric

Ferroelastic

Ferrotoroidal,

Symmetry breaking: Para $\rightarrow$ Ferroic

Ferroelastics

- Elastic heterogeneities: habit planes, twin boundaries
:polydomains (aggregates)

Criticality and the piezoelectric response of ferroelectrics

Critical point in rhombohedral [111] poled $\text{Pb}(\text{Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3\text{-PbTiO}_3$ (PMN-PT)

Z. Kutnjak *et al.*, Nature **441**, 956 (2006)
M. Iwata *et al.*, J. Phys. Soc. Jpn. **77**, 034703 (2008)

Triple-tricritical point in $\text{Ba}(\text{Ti}_{0.8}\text{Zr}_{0.2})\text{O}_3\text{-(Ba}_{0.7}\text{Ca}_{0.3})\text{TiO}_3$ (BZT-BCT)

W. Liu and X. Ren, Phys. Rev. Lett. **103**, 257602 (2009)

- Piezoelectric response near a **critical point**

Toroidal & Magnetoelectric Glass

- Collusion of disorder and **anisotropic**, long range interactions ($G=E \times B$).
- Toroidal dipolar interaction **short range**.
- Toroidal state is **more likely** to be glassy; toroidal anisotropy.
- Thus pure toroidal order **more difficult** to observe directly: $\text{LiCo}(\text{PO}_4)_3$.
- Multiglass: Fe_2TiO_5 (S. Sharma et al., PRB 2014).
- **Simulations** with short range interaction.

MAGNETOELECTRIC COOLING BY ME_H IN NMTO

Y. Yamaguchi
And T. Kimura,
Nature Commun.
June (2013)

TOROIDAL FROZEN STATE: MAGNETOELECTRIC CONTROL