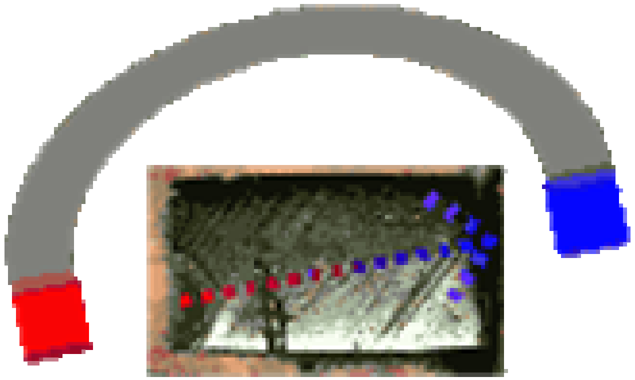
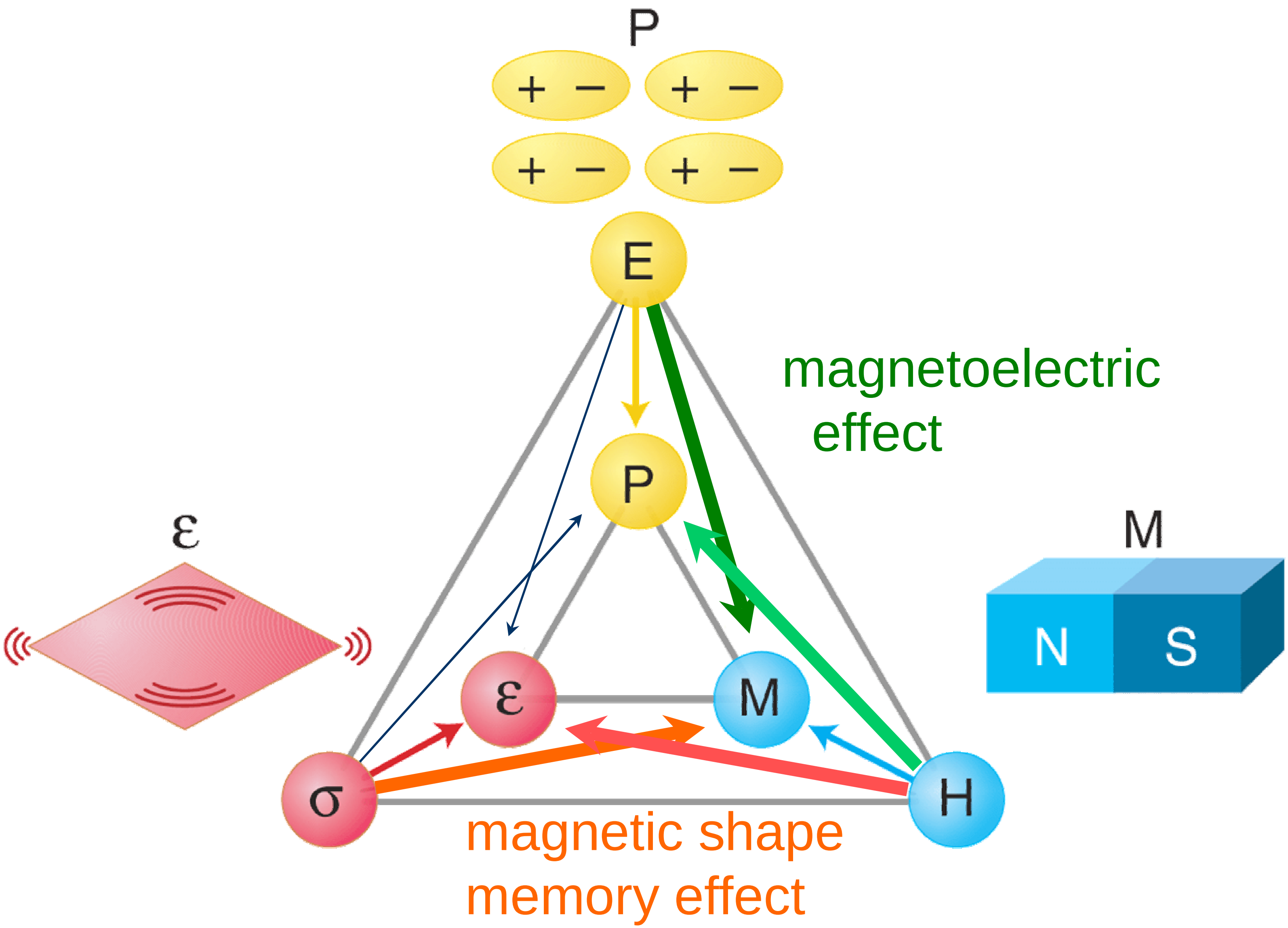
Magnetic Shape Memory Alloys



www.adaptamat.com

- Magnetically Induced Martensite (MIM)
- Magnetically Induced Reorientation (MIR)
- Requirements for actuation
- “Exotic” materials

German Priority Program SPP 1239:
“Modification of Microstructure and Shape of solid Materials by an external magnetic Field”
www.MagneticShape.de


P
+ −
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E
P
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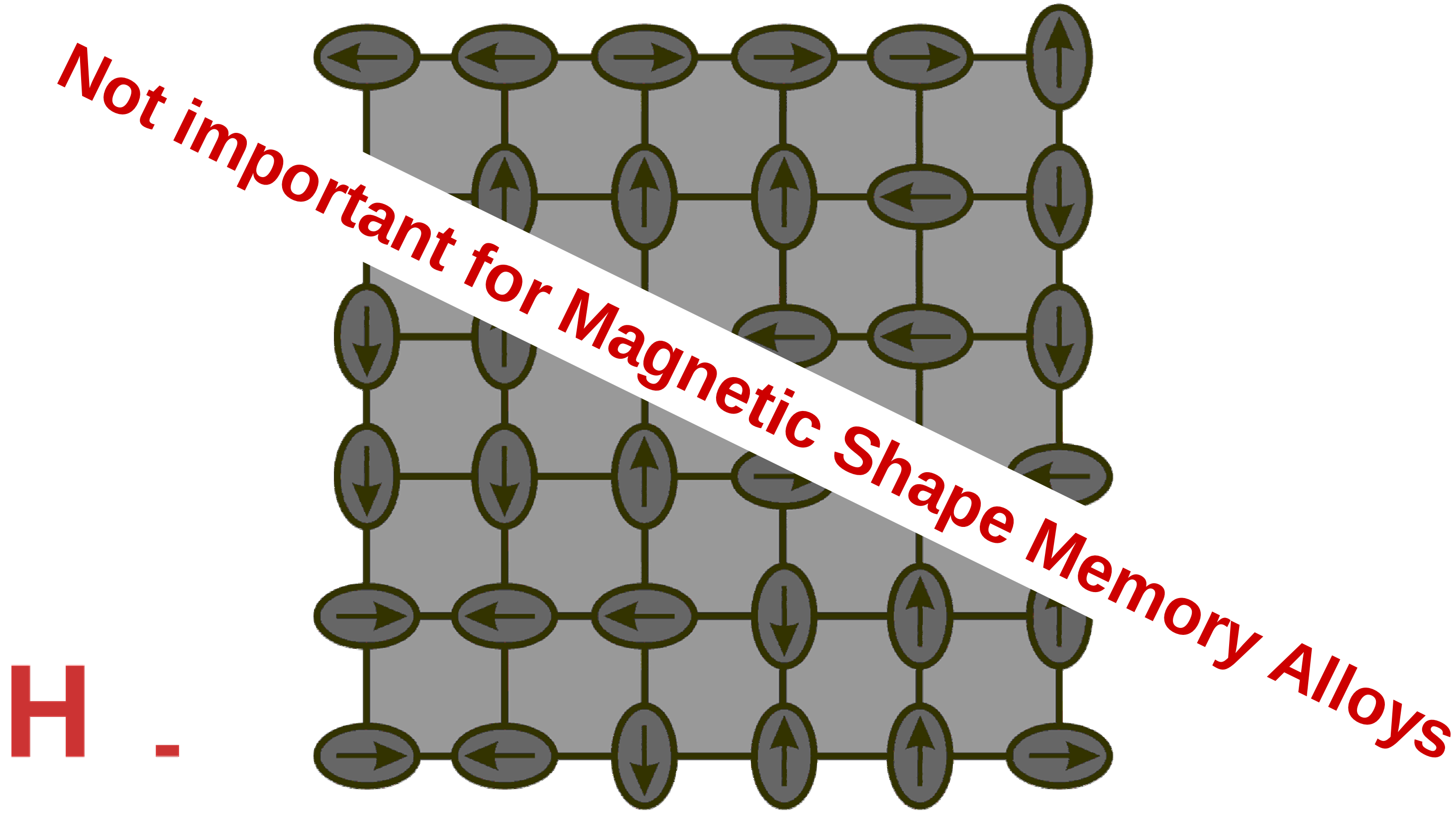
σ
H
ε
M
N
S
magnetoelectric effect
magnetic shape memory effect

Anisotropic magnetostriction



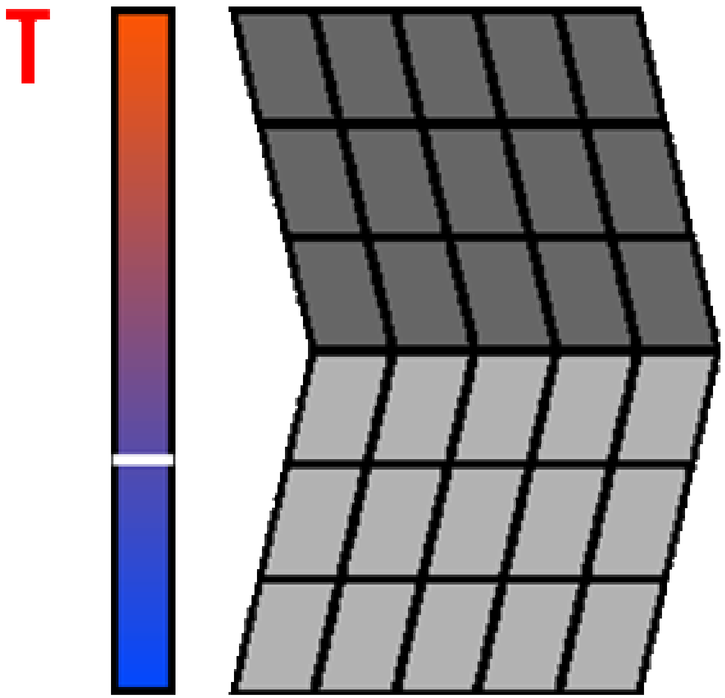
- Strain < 0.24 %
+ High frequency
+ Low magnetic field

- ***Single ion effect*** *(spin-orbit coupling) – no collective phenomenon*

Martensitic transformation

$T > T_M$:
Austenite
(high symmetry)

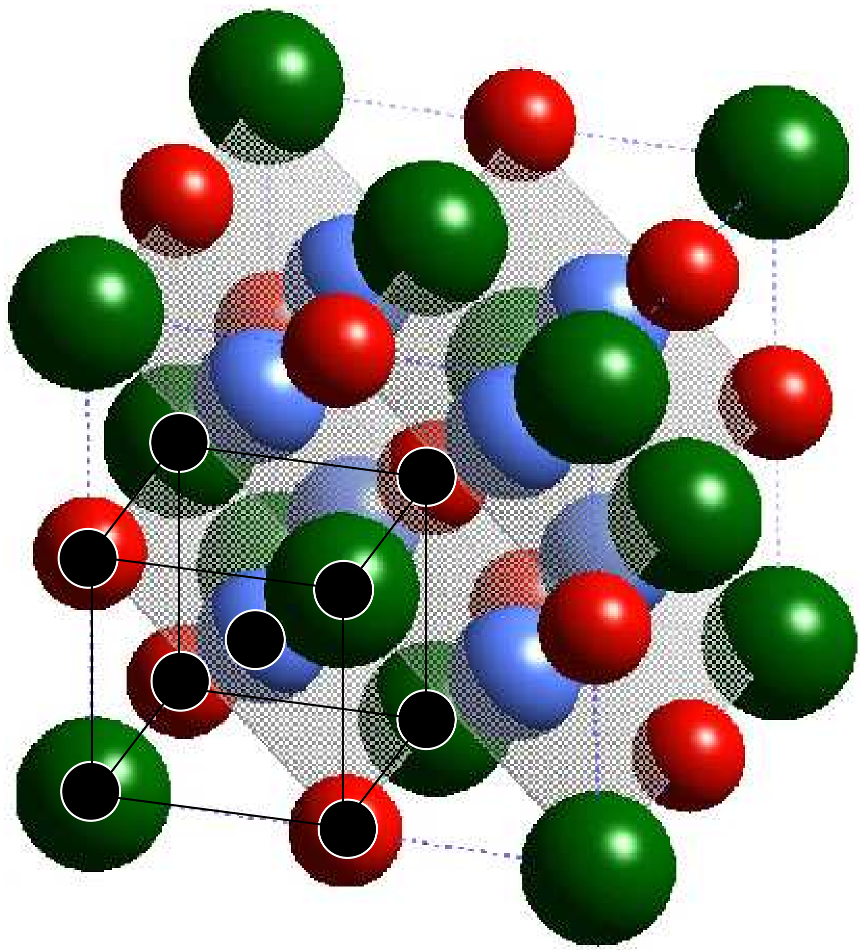
$T < T_M$:
Martensite
(low symmetry)



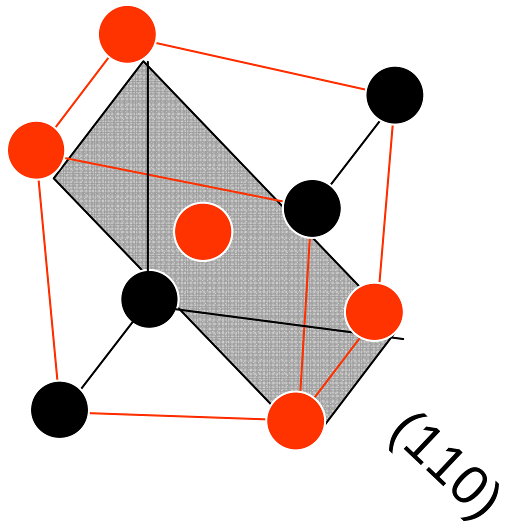
- No diffusion, reversible
- Twinned microstructure of martensite
- Thermal actuation
  - ⇒ conventional shape memory effect

+	Strain > 5%
+	High forces
-	Low frequency

Prototype Ni-Mn-Ga, Shearing



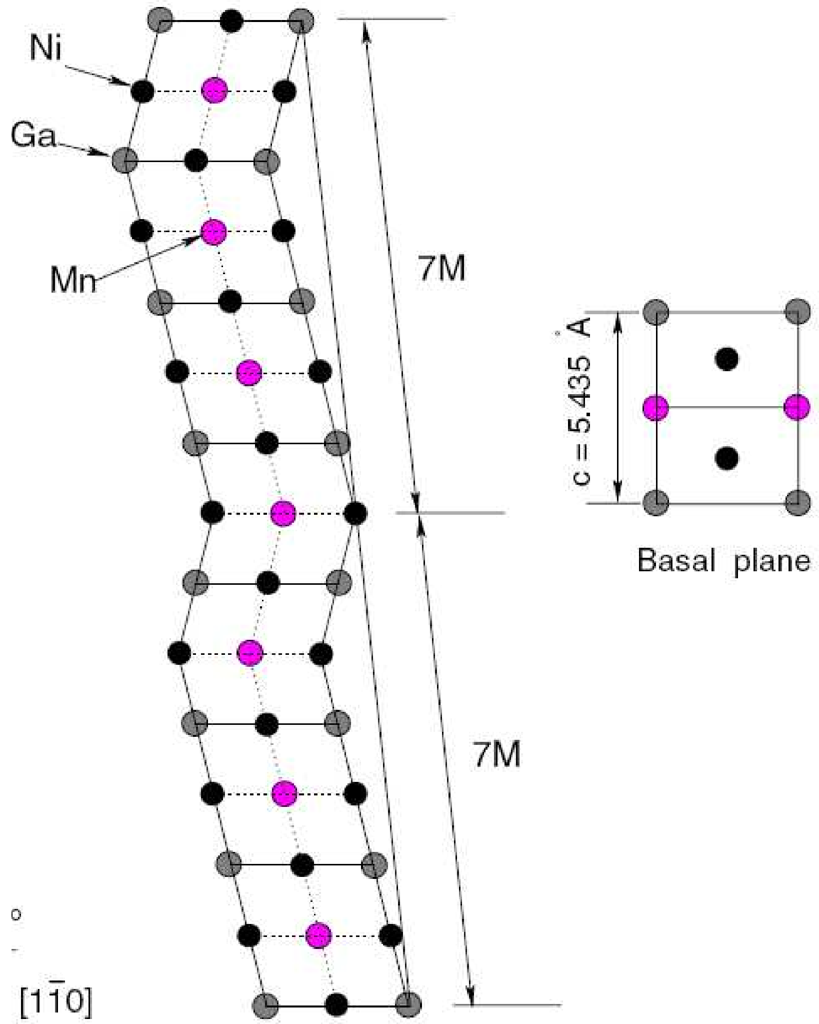
$Ni_{2+x}Mn_{1-x}Ga$
$L2_1$



bcc - sheared

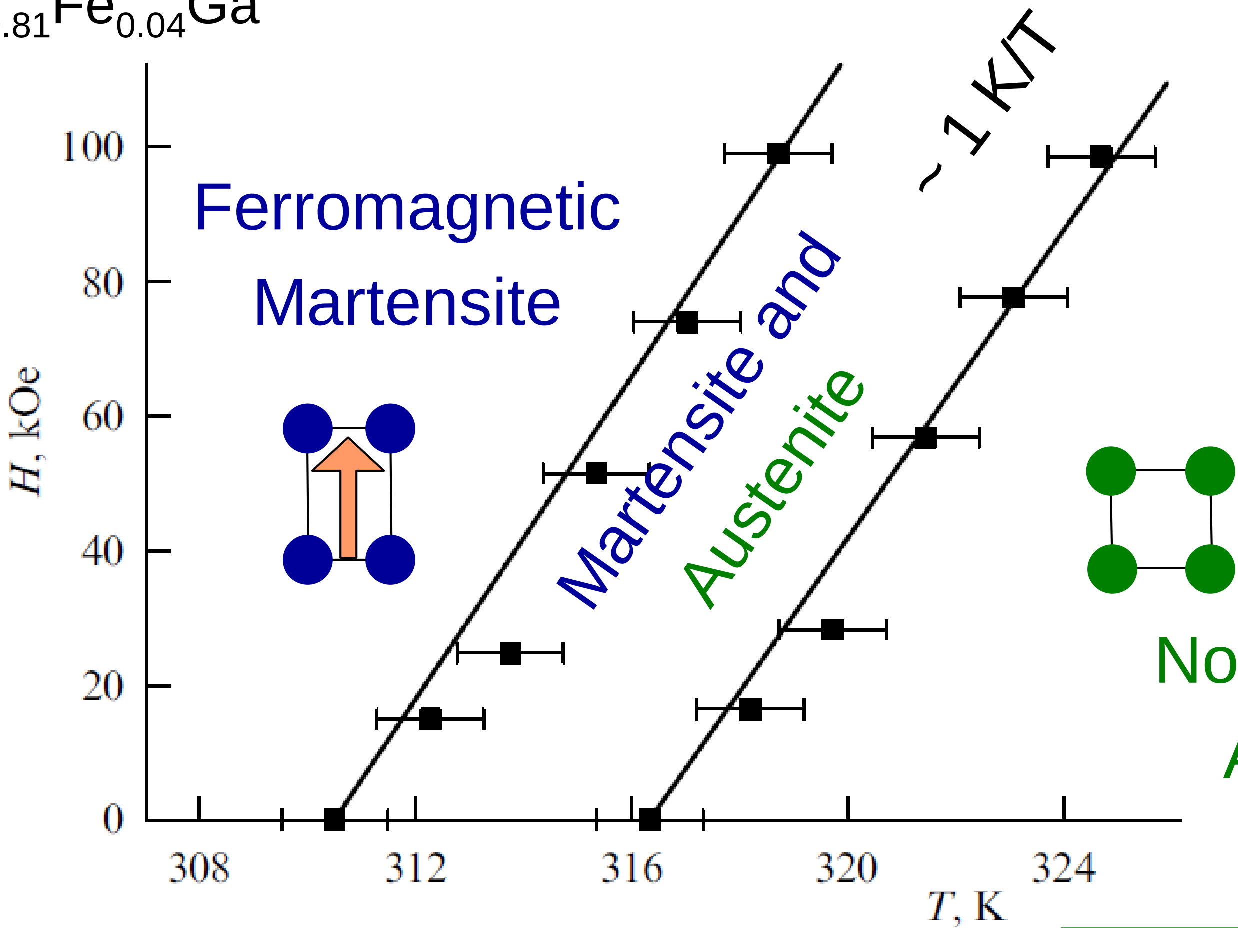
Why are structures instable?
→ Phonon spectra

7M Martensite



Martensitic transformation of magnets

$Ni_{2.15}Mn_{0.81}Fe_{0.04}Ga$



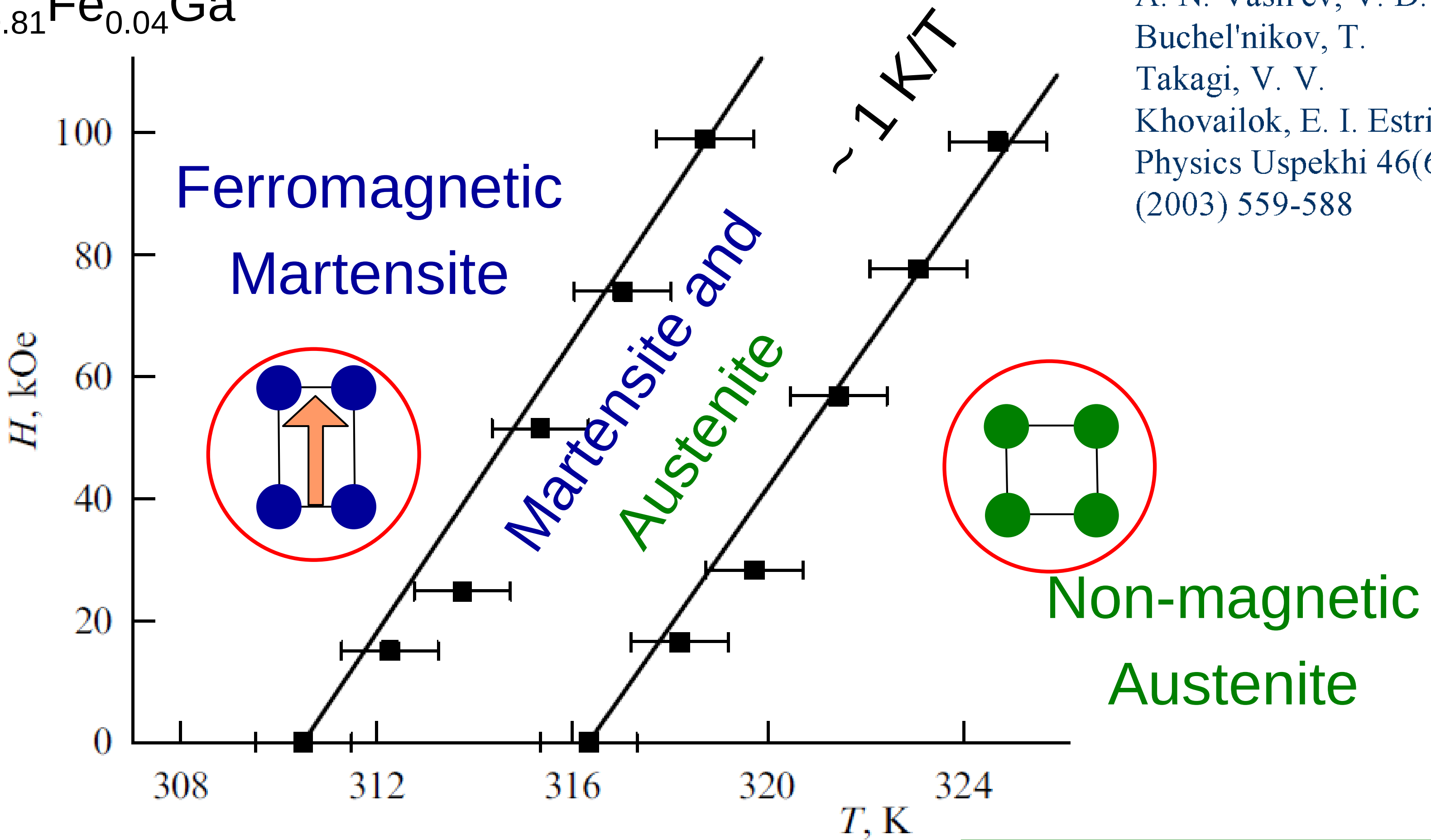
A. N. Vasil'ev, V. D. Buchel'nikov, T. Takagi, V. V. Khovailok, E. I. Estrin, Physics Uspekhi 46(6) (2003) 559-588

- Modification of structure and shape by a magnetic field

- High magnetic field >> 1 T
- Narrow temperature regime

Martensitic transformation of magnets

$Ni_{2.15}Mn_{0.81}Fe_{0.04}Ga$



A. N. Vasil'ev, V. D. Buchel'nikov, T. Takagi, V. V. Khovailok, E. I. Estrin, Physics Uspekhi 46(6) (2003) 559-588

- Modification of structure and shape by a magnetic field

- High magnetic field >> 1 T
- Narrow temperature regime

Magnetically Induced Martensite (MIM)

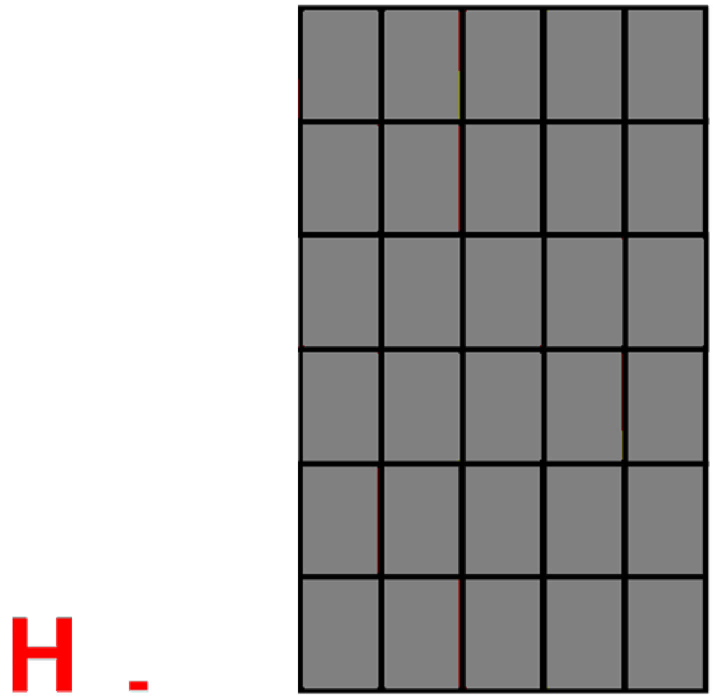
Magnetic field favors
ferromagnetic phase

Clausius Clapeyron:

$$\frac{dT}{dH} = \frac{\Delta J}{\Delta S}$$

ΔJ: magn. polarization difference in martensite and austenite state

ΔS: entropy difference



- Magnetic actuation
- Latent heat (magnetocaloric effect): here a problem

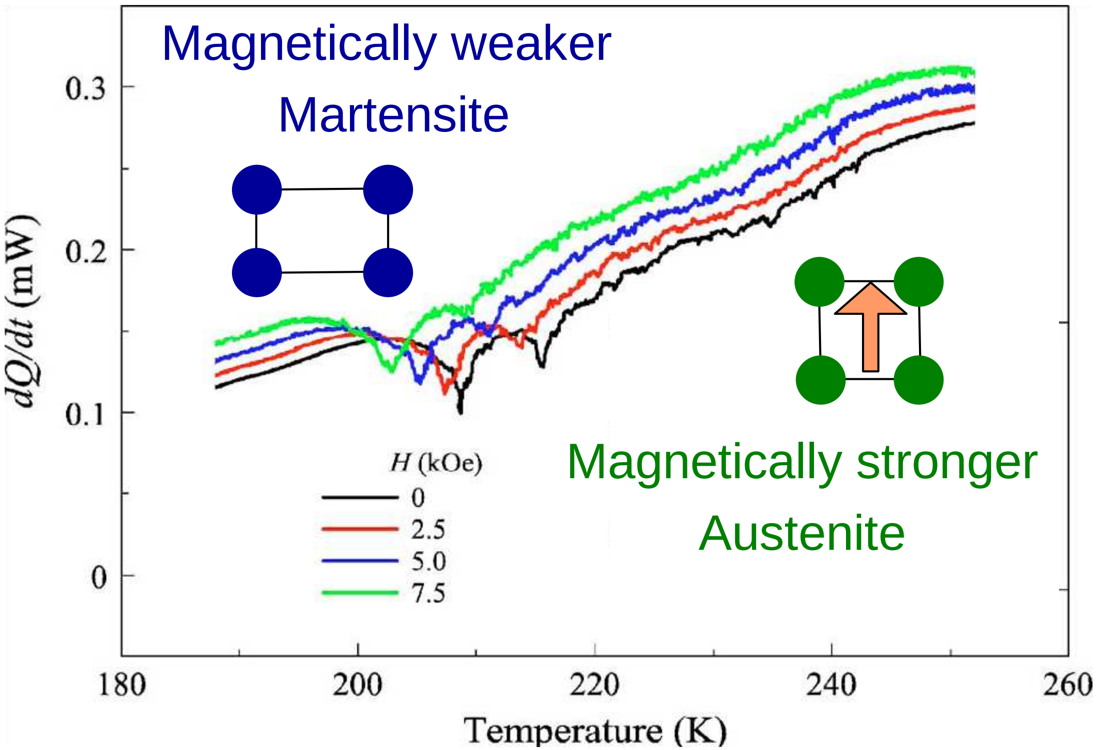
\+ Remote actuation

New Materials: Inverse Transformation

Ni-Mn-In

Magnetic field favors high temperature austenite because its ferromagnetism is stronger than that of martensite

DSC:



T. Krenke, M. Acet, E. F. Wassermann, X. Moya, L. Manosa, A. Planes, Phys. Rev. B 73 (17) (2006) 174413

- Shift of M_S by -8 K/T
- Large magnetocaloric effect

Magnetically Induced Austenite (MIA)

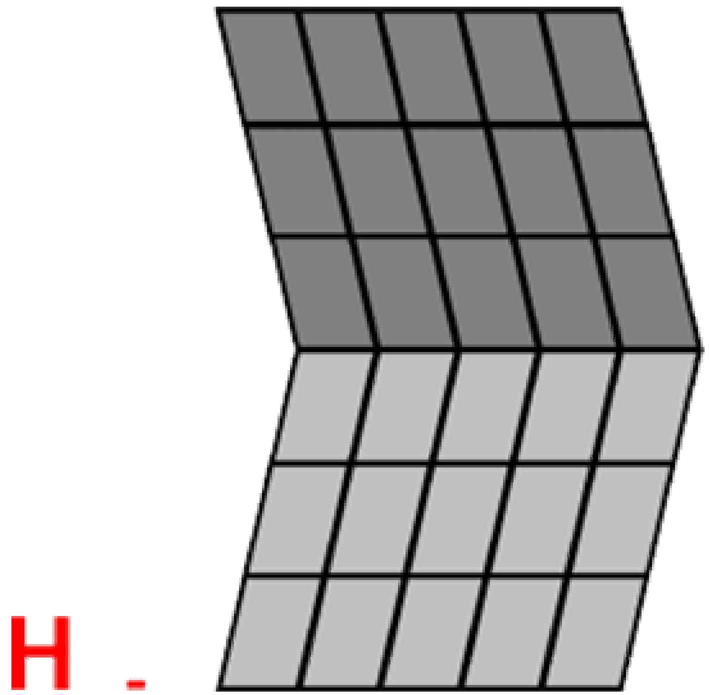
Magnetic field favors
ferromagnetic phase

Clausius Clapeyron:

$$\frac{dT}{dH} = \frac{\Delta J}{\Delta S}$$

ΔJ: magn. polarization difference in martensite and austenite state

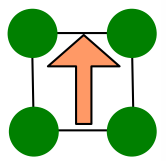
ΔS: entropy difference



Negative $\Delta J \rightarrow H$ stabilizes austenite

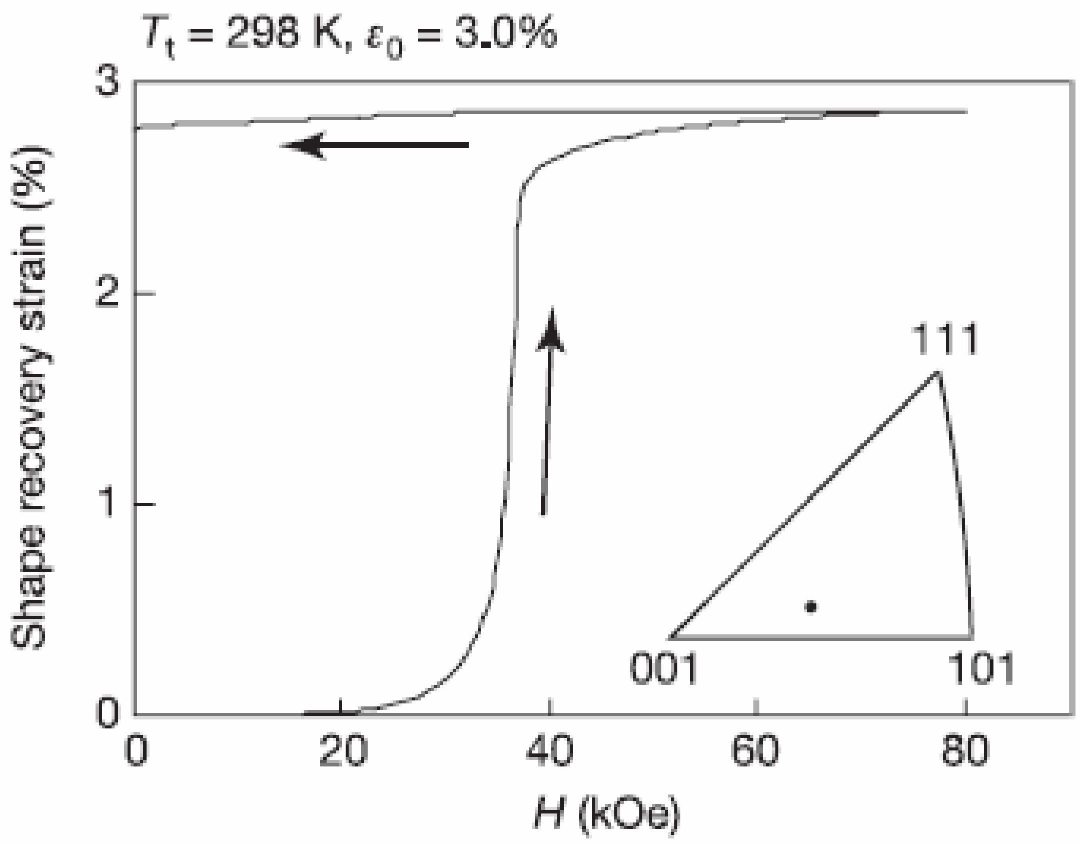
Magnetically Induced Austenite (MIA)

$Ni_{45}Co_5Mn_{36.7}In_{13.3}$

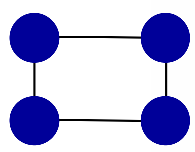


FM

Austenite



R. Kainuma et al.
Nature 439 (2006) 957



NM

Martensite

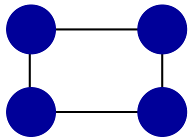
- Hysteresis may inhibit reversibility !

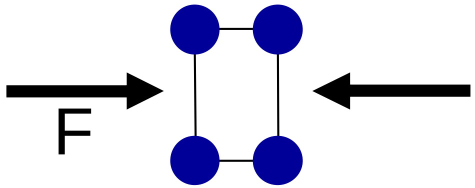
+	Strain ~ 3%
	Hysteresis losses?
+	No anisotropy needed

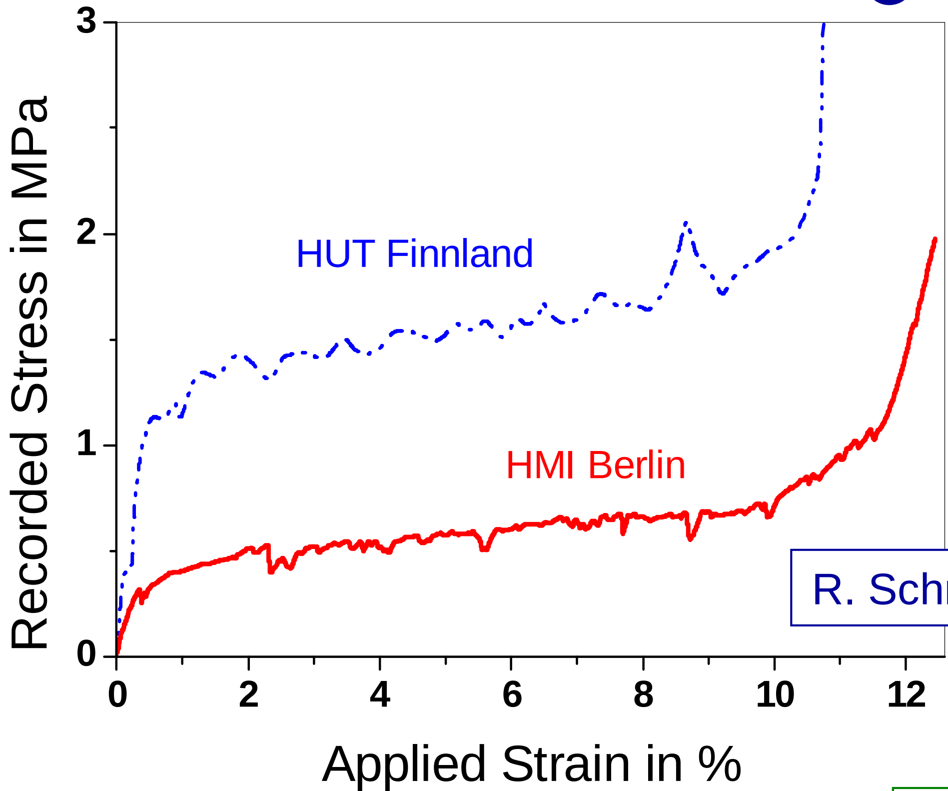
Rubber like behavior

Ni-Mn-Ga, 7M

At const $T < T_M$







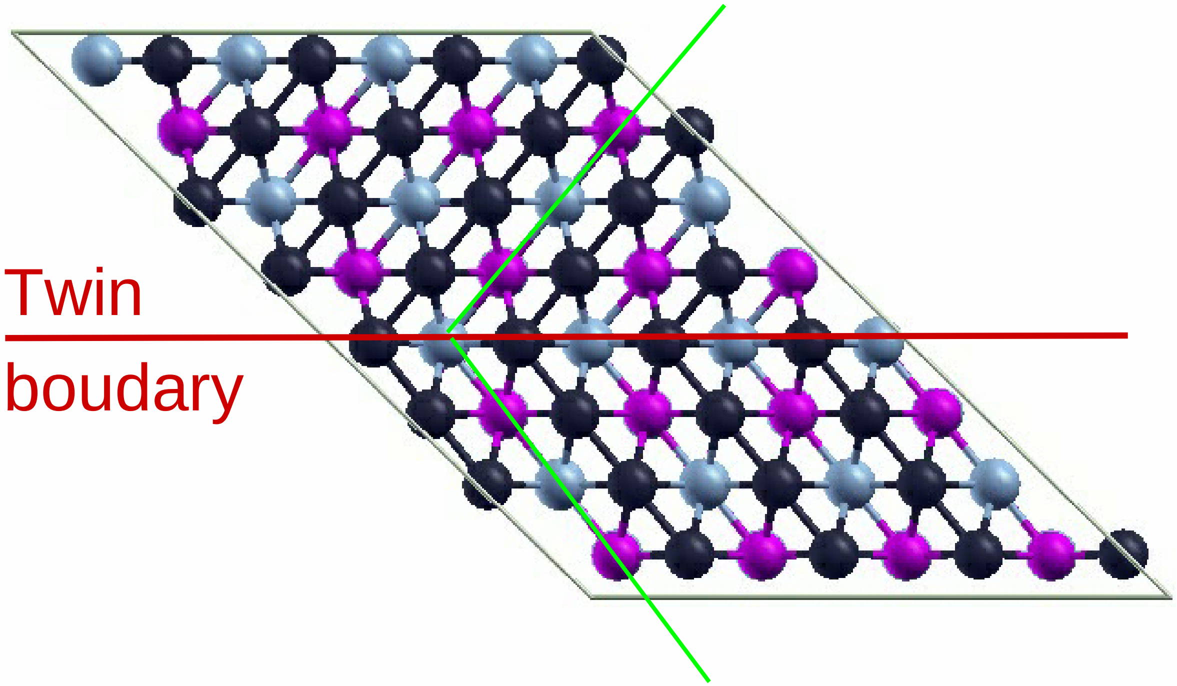
R. Schneider, *HMI Berlin*

- Easy movement of twin boundaries (~ MPa)

- Little pinning of twin boundaries at defects

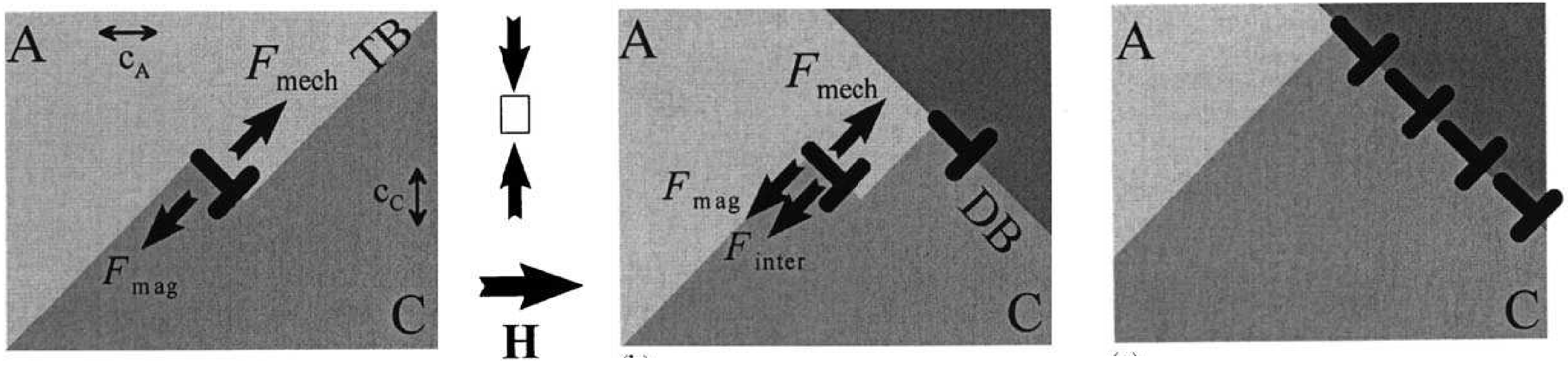
Twin boundary movement

A3: P. Entel,
U. Duisburg-Essen



- Only highly symmetric twin boundaries are highly mobile
- But a collective movement would require to move 10^{23} atoms simultaneously...

Microscopic view of twin boundary movement



- Dislocation (step + screw) as elemental step of twin boundary movement

P. Müllner et al., JMMM **267** (2003) 325

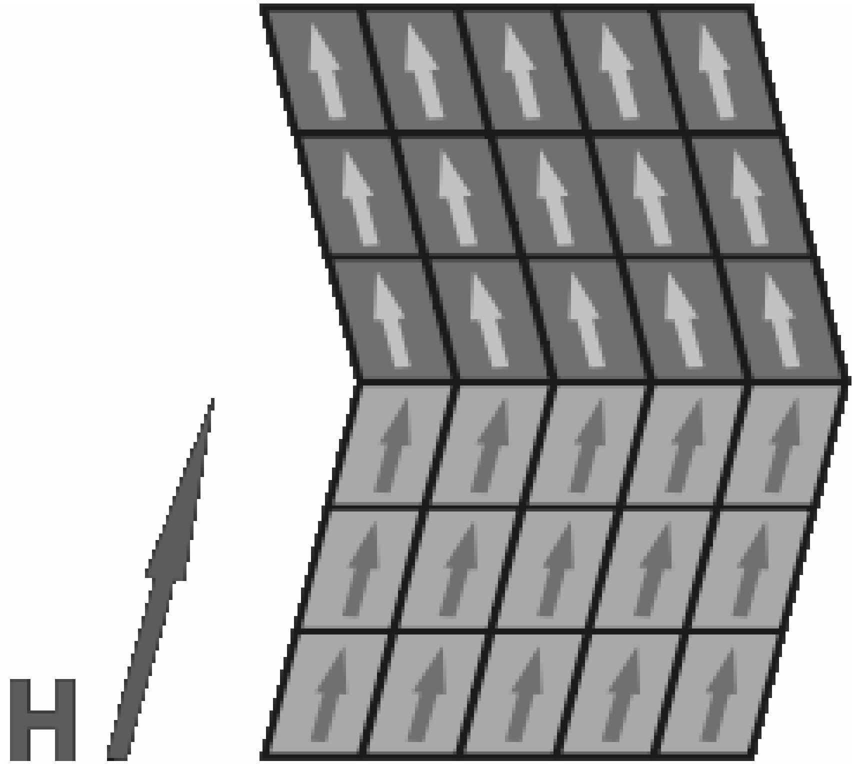
- „Intrinsic" Peierls stress to move Burgers vector ~ 10^{-13} Pa

S. Rajasekhara, P. J. Ferreira Scripta Mat. 53 (2005) 817

Magnetically Induced Reorientation (MIR)

Twin boundary movement

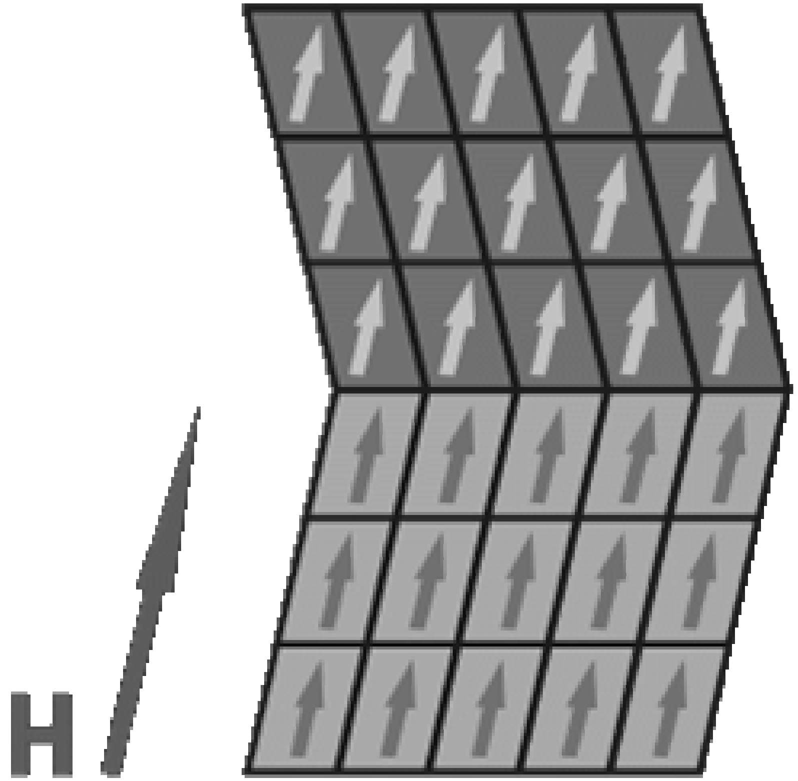
No phase transition,
affects only microstructure



Requires:

- Non-cubic phase
- High magnetocrystalline aniosotropy
- Easily movable twin boundary

++ **Strain ≤ 10 % !**
+ High frequency

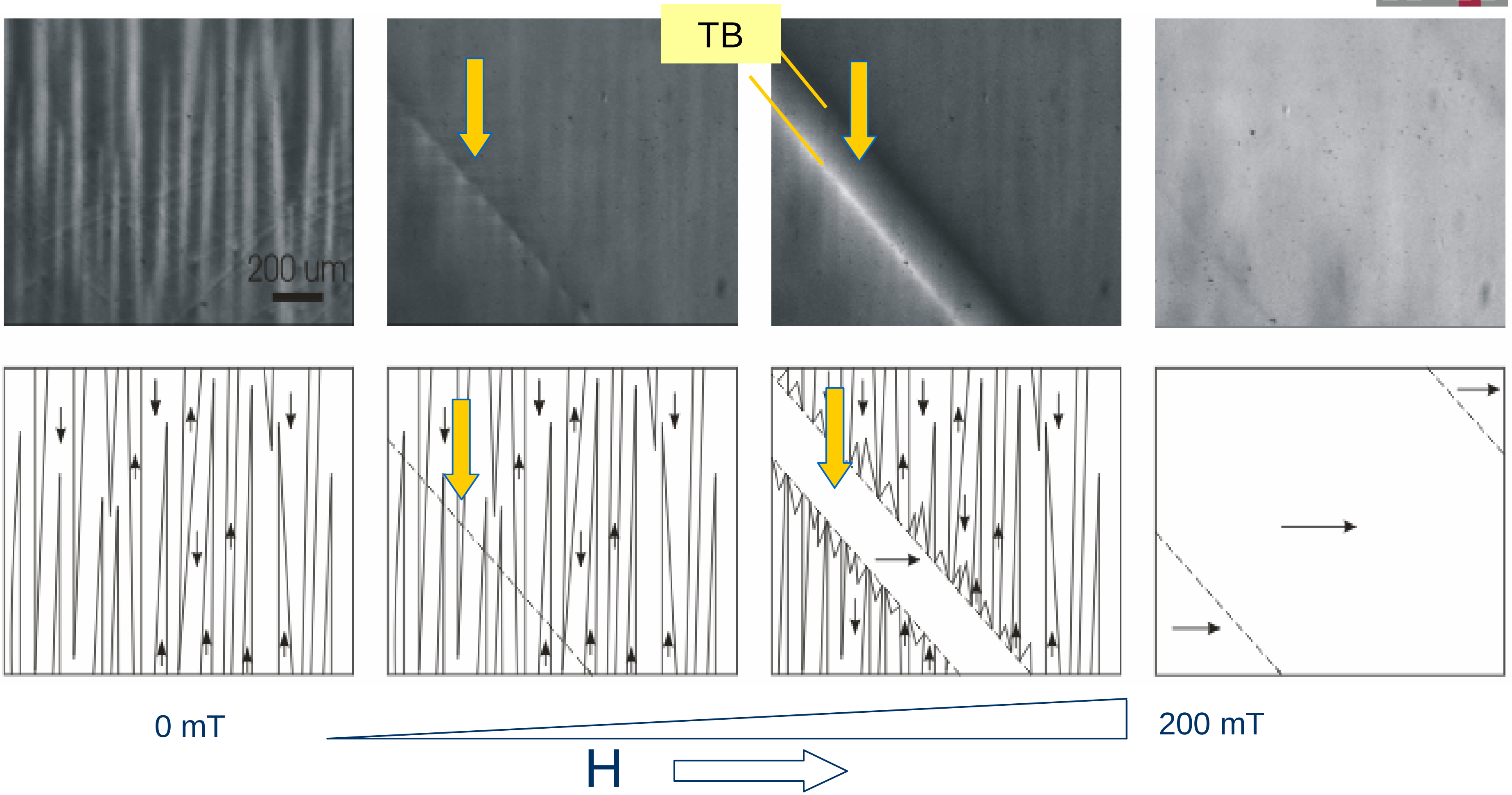


- Rotation of magnetization must be avoided

  ⇒ high magnetocrystalline anisotropy needed

Domain and twin boundary dynamics

Y.W. Lai, N. Scheerbaum, D. Hinz, O. Gutfleisch, R. Schaefer, L. Schultz, J. McCord, Appl. Phys. Lett. **90** (2007) 192504

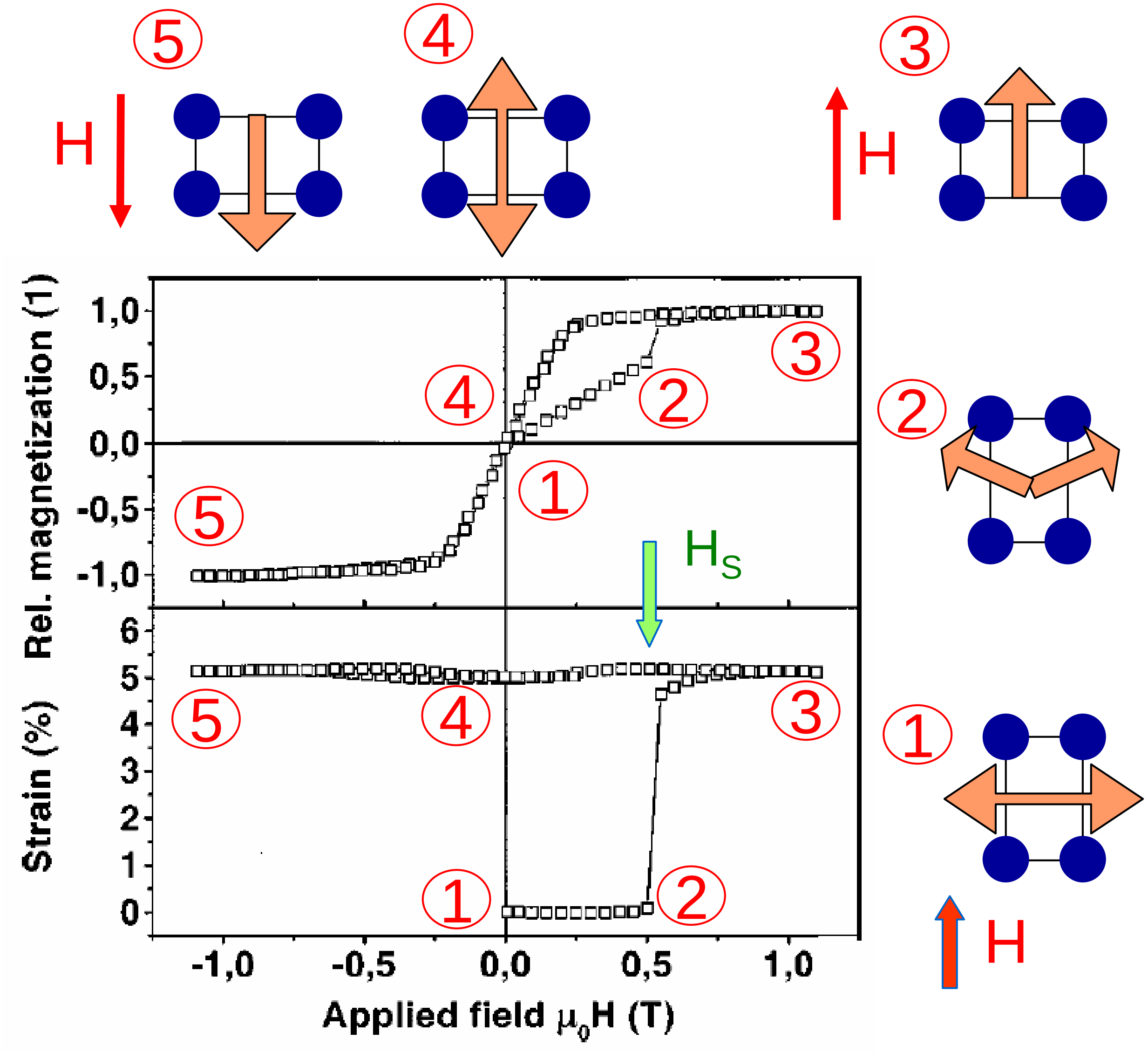


- Magnetic field moves twin boundary instead of magnetization rotation

Integral measurement of strain and magnetization

Ni-Mn-Ga

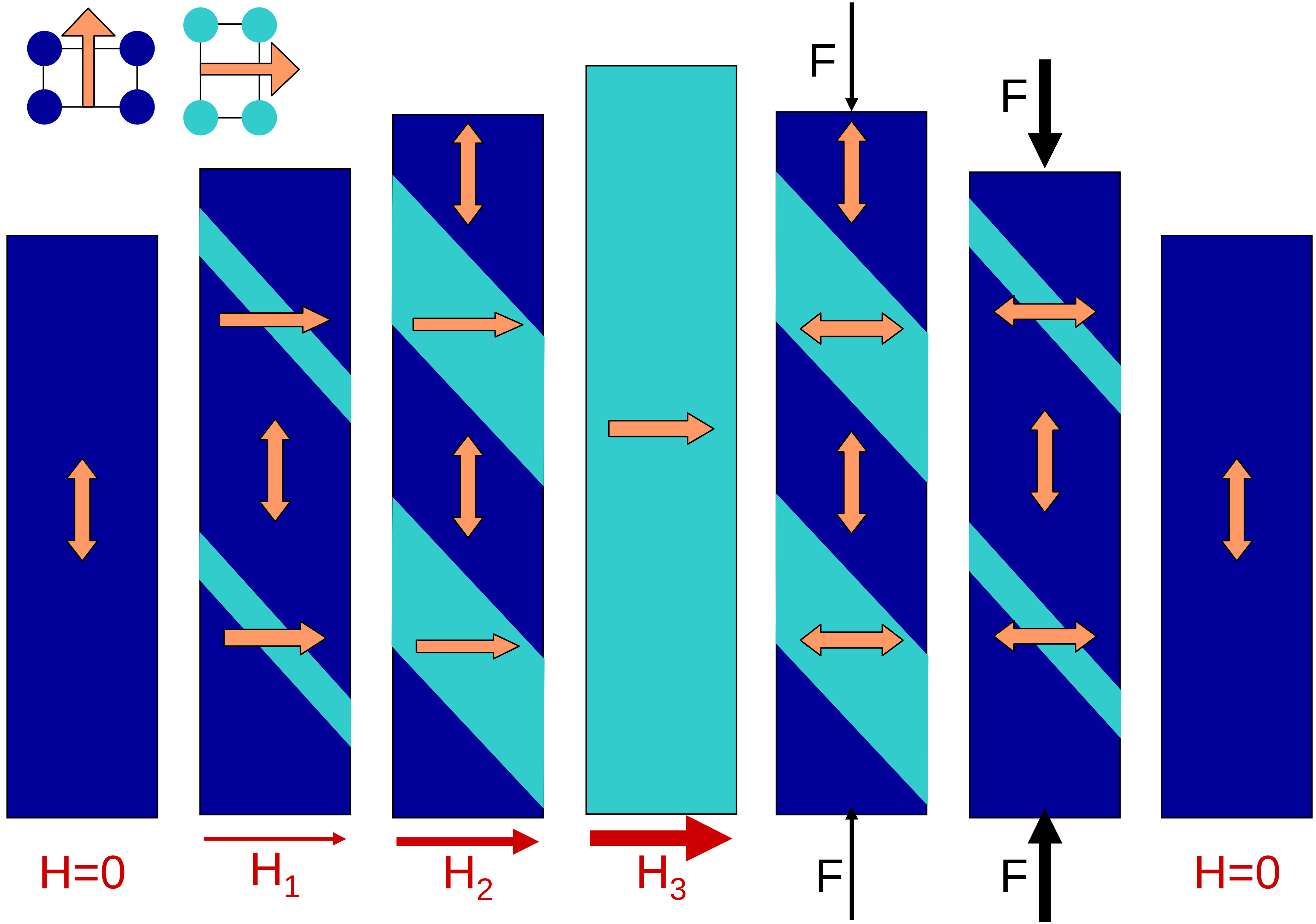
5M



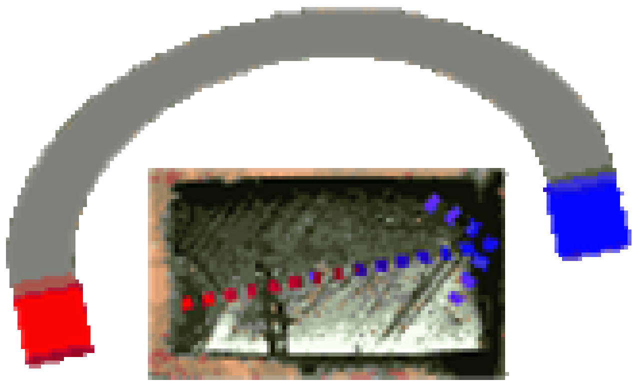
O. Heczko, L. Straka, N. Lanska, K. Ullakko, J. Enkovaara, J. Appl. Phys. **91**(10) (2002) 8228

- moderate switching field H_S < 1 T

Setup of a linear actuator



Magnetic Shape Memory Alloys



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Beneficial conditions for MIR

Intrinsic properties (composition, phase)

- High martensitic transformation temperature $\Rightarrow$ high application temperature
- High magnetocrystalline anisotropy $\Rightarrow$ avoids rotation of magnetization
- High magnetization $\Rightarrow$ high blocking stress
- Large maximum strain $\varepsilon_0 = 1 - c/a$

Extrinsic properties (microstructure, texture)

- High strain $\varepsilon < \varepsilon_0$
- Low switching field $H_S < H_A$
- Easily moveable twin boundaries $\Rightarrow$ rubber like behavior

Aim: high strain in low magnetic fields

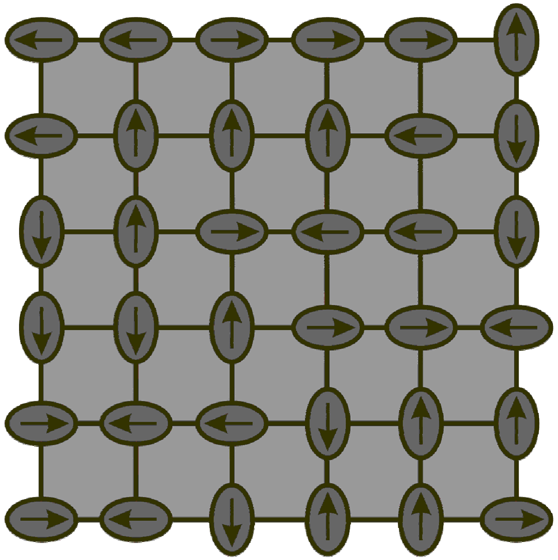
What is essential for the MSM effect?

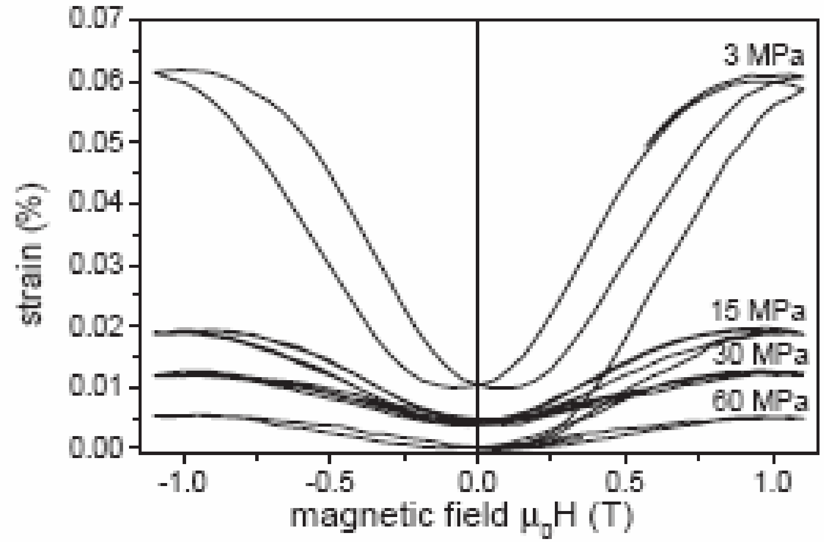
	Not fulfilled for:
• Martensitic transformation	Tb, Dy, *Re*Cu_2
• Ferromagnetism	*Re*Cu_2, $La_{2-x}Sr_xCuO_4$
• High uniaxial magnetocrystalline anisotropy	$Fe_{70}Pd_{30}$, Ni-Mn-In
• High magnetostriction	Ni-Mn-Ga
• Chemical ordering	$Fe_{70}Pd_{30}$, Tb, Dy

Anisotropic magnetostriction

Constrained 5M NiMnGa single crystals

H -



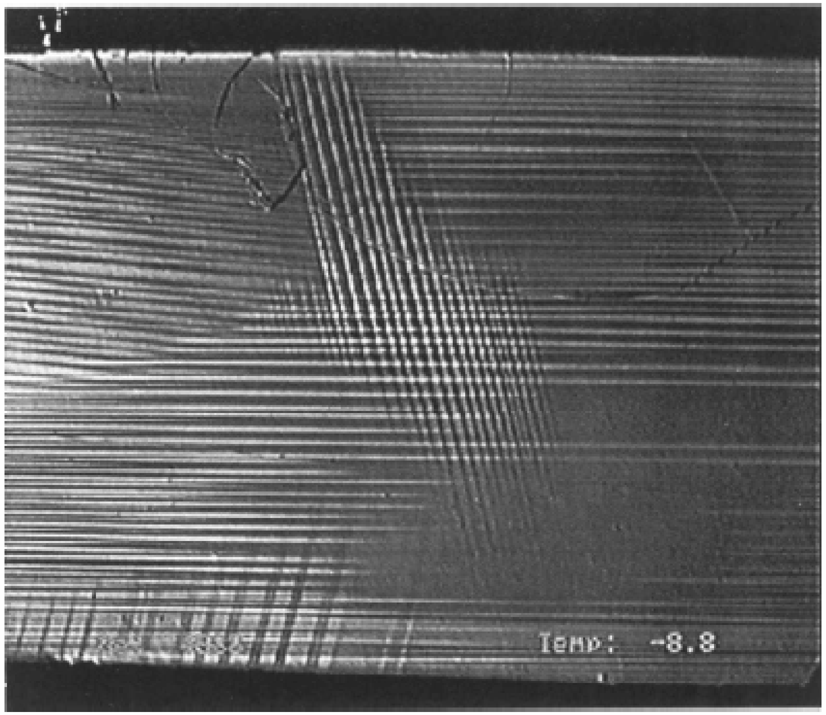


$\lambda_S = -50$ ppm

O. Heczko, J. Mag. Mag. Mat. 290-291 (2005) 846

- Not appropriate to describe threshold like switching (Reorientation or Martensitic transformation)

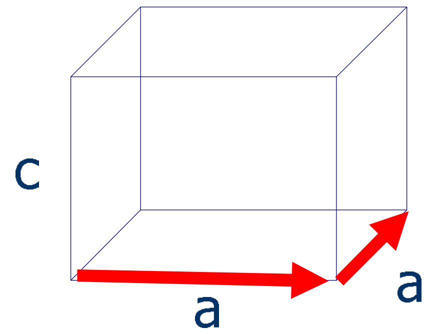
$Fe_{70}Pd_{30}$



Austenite: fcc

Martensite: fct, c/a <1

two easy axis || a



R.D. James, M. Wuttig
Phil. Mag. **77** (1998) 1273

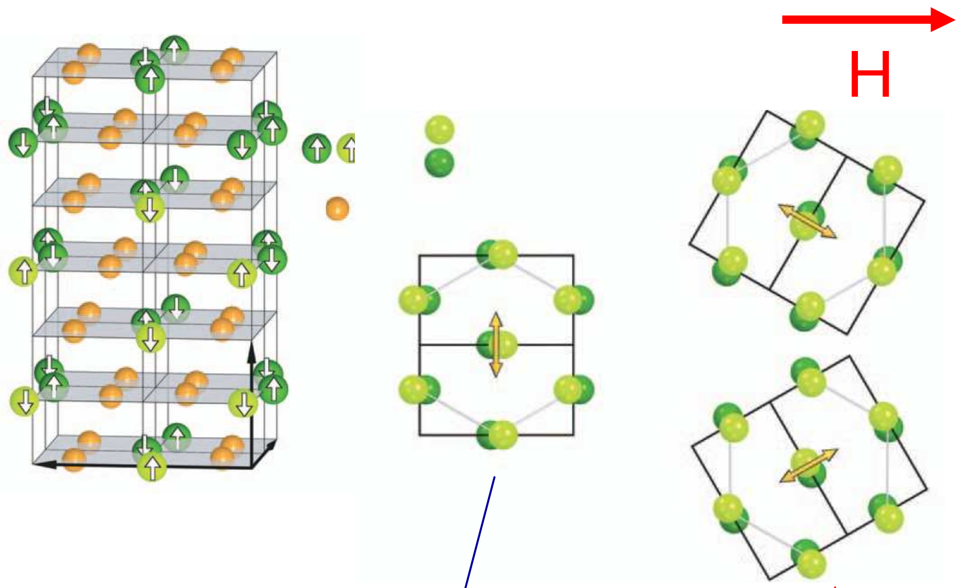
J. Cui, T.W. Shield, R.D. James,
Acta Mat. **52** (2004) 35

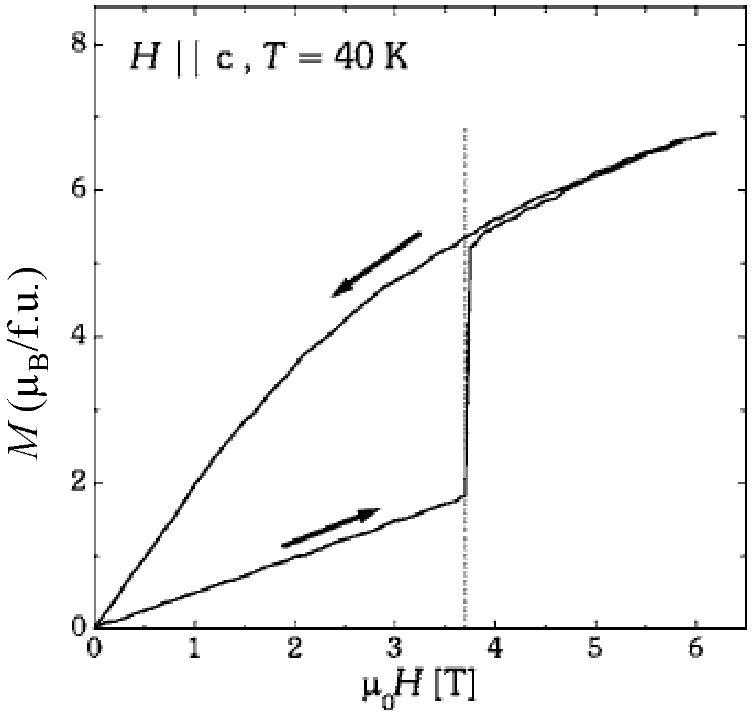
- No **uni**axial anisotropy needed
- No chemical ordering

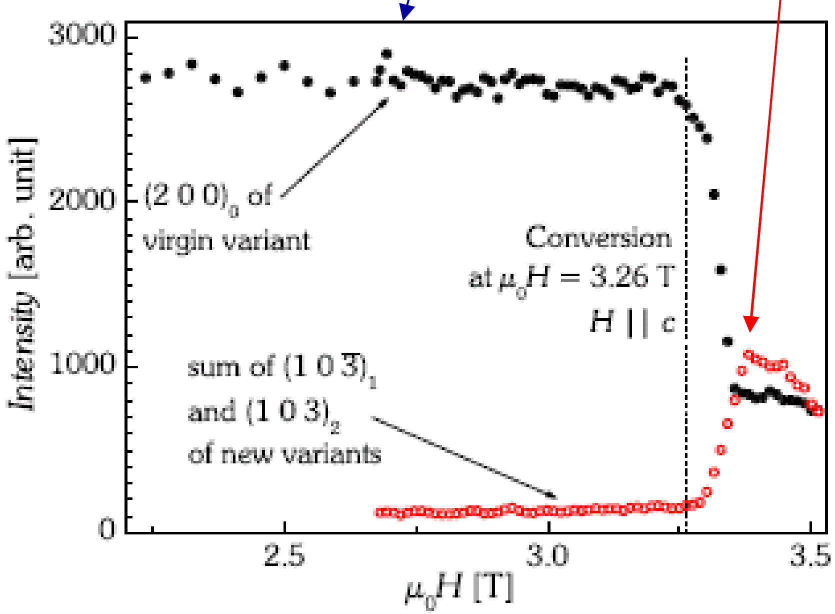
$Tb_{0.5}Dy_{0.5}Cu_2$

S. Raasch, et al. PRB **73** (2006) 64402

- no martensitic transformation
- orthorhombic (pseudohexagonal, 3 variants)





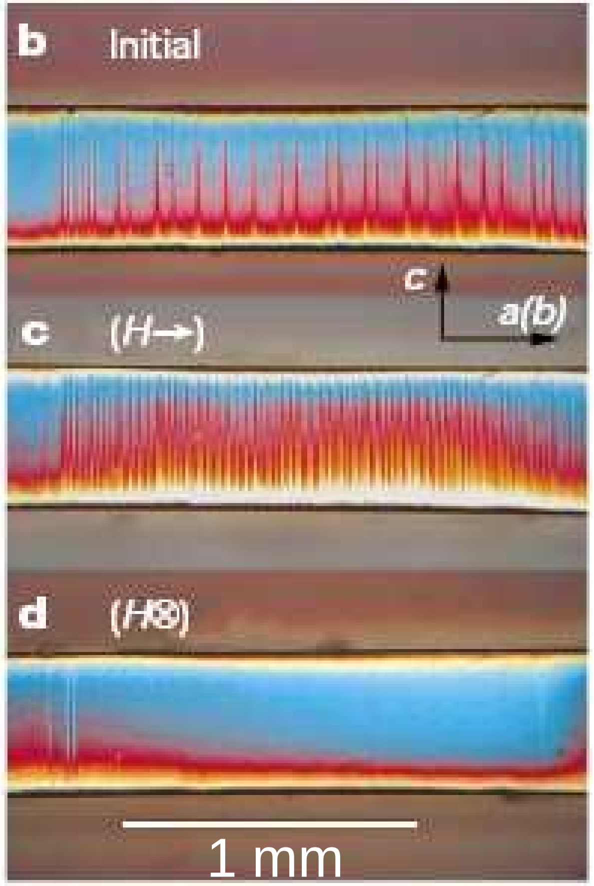


- Canted magnetic order
- 1.5 % strain at 3.2 T by reorientation

$La_{2-x}Sr_xCuO_4$ (LSCO)

A. N. Lavrov, S. Komiya, Y. Ando, Nature **418** (2002) 385

A. N. Lavrov, Y. Ando, S. Komiya, I. Tsukada, Phys. Rev. Lett. **87** (2001) 17007



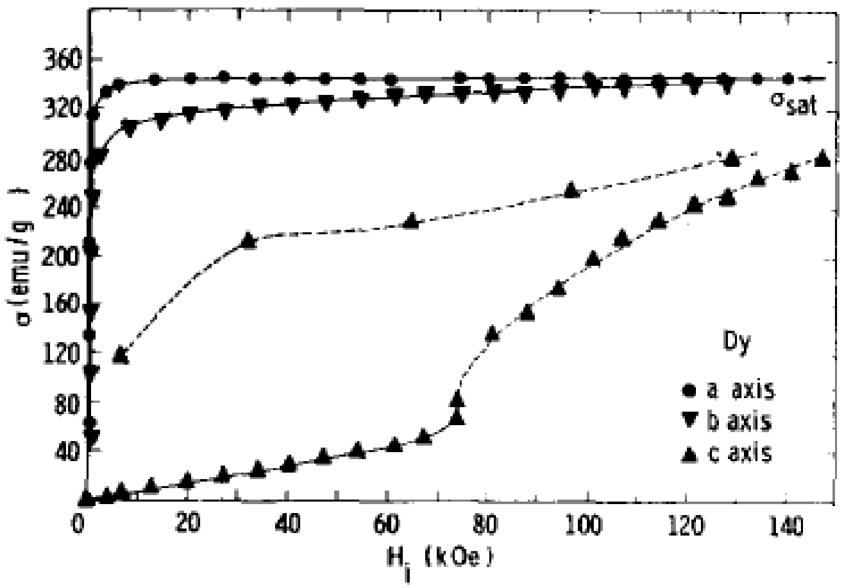
H = 14 T

RT

1% strain

- Orthorhombic, twinning in ab plane, b axis (red domains) aligns parallel to magnetic field
- **Antiferromagntic**, weak ferromagnetic moment

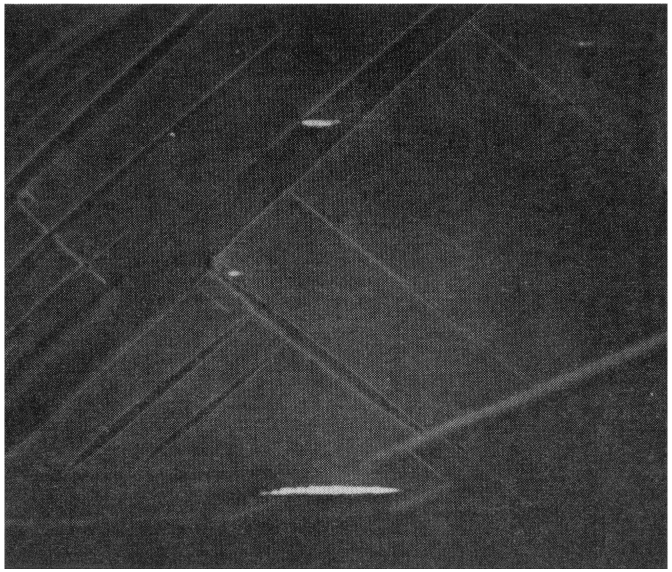
Dy single crystal at 4 K



8% strain in Tb (40 T, 4K)

S. Chikazumi et al. IEEE Trans. Mag. MAG-5(3) (1969) 265

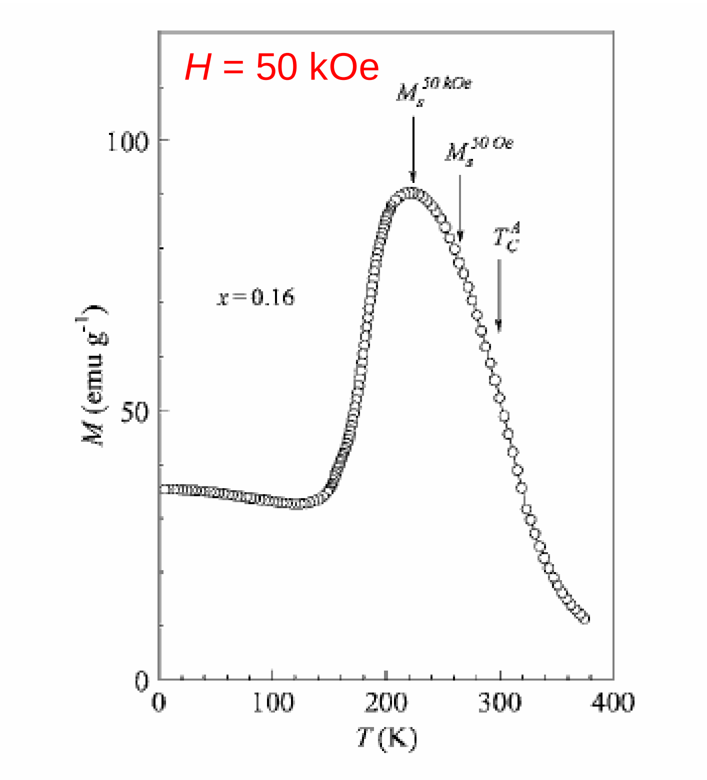
J. J. Rhyne et al. J. Appl. Phys. **39**(2) (1968) 892



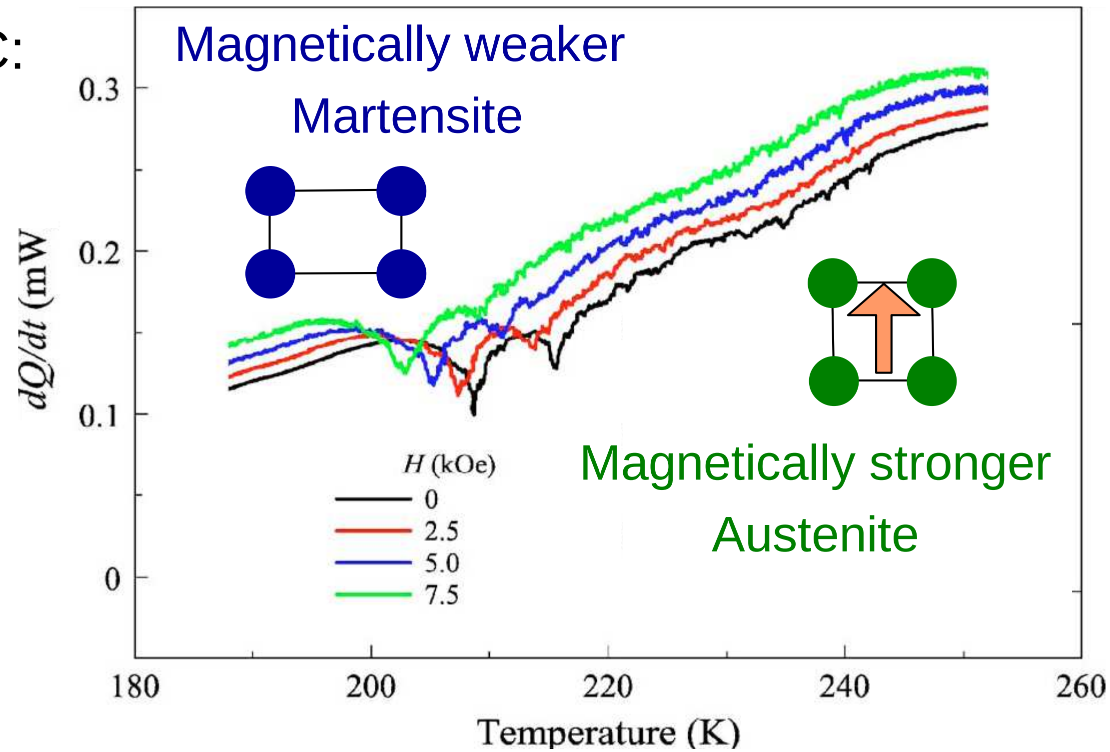
- Pure elements

H. H. Liebermann, C. D. Graham, Acta Met. **25** (7) (1977) 715

Magnetic field favors high temperature austenite because its ferromagnetism is stronger than that of martensite



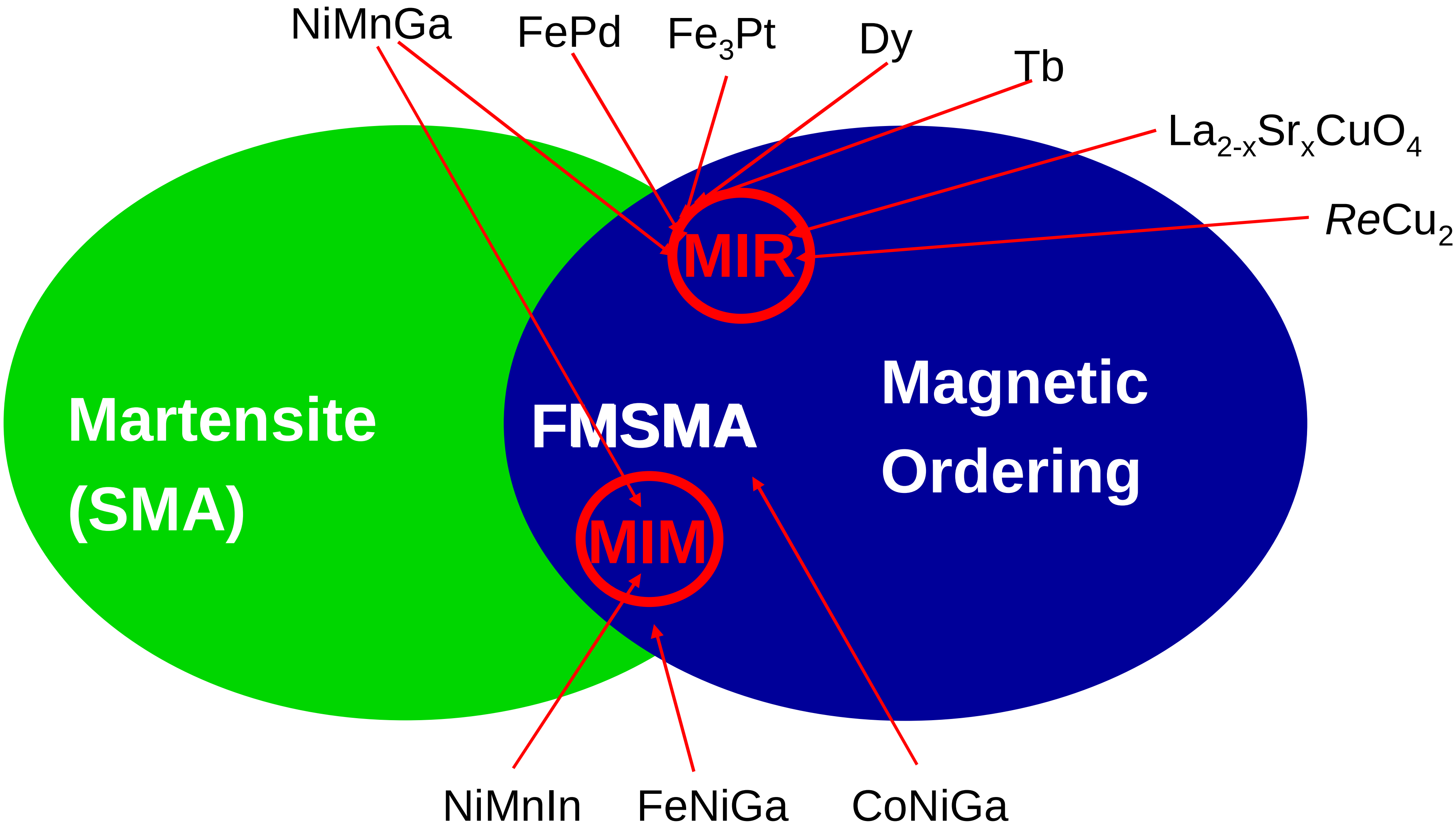
DSC:



- No significant magnetocrystalline anisotropy (cubic ferromagnet)

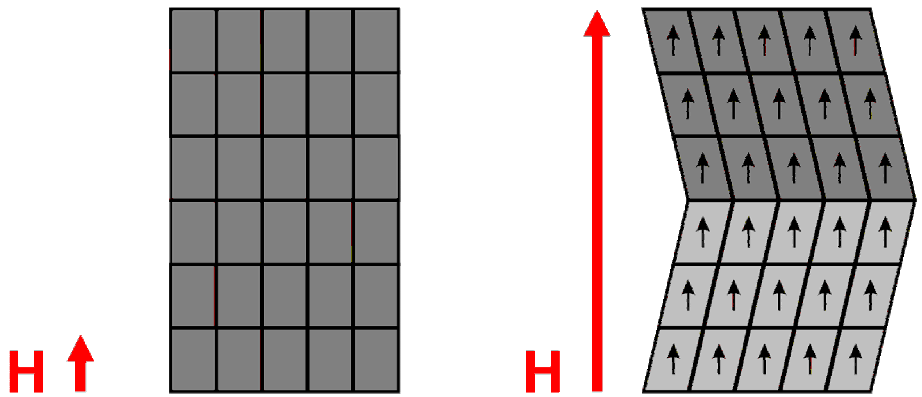
T. Krenke, M. Acet, E. F. Wassermann, X. Moya, L. Manosa, A. Planes, Phys. Rev. B **73** (17) (2006) 174413

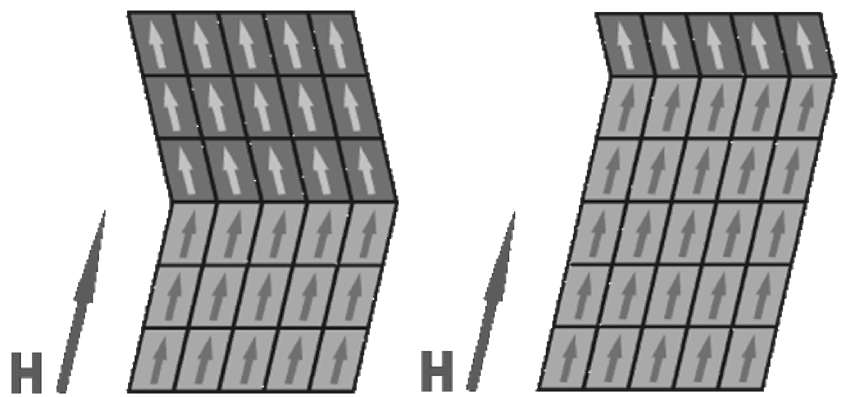
Magnetic Shape Memory Alloys



Magnetic Shape Memory Alloys

Magnetically **I**nduced **M**artensite (MIM)	**M**agnetically **I**nduced **R**eorientation (MIR)
Essential	
Martensitic transformation with large ΔJ	Magnetocrystalline anisotropy Easily movable twin boundaries
Beneficial	
Low Hysteresis Low ΔS Transformation around RT	Ferromagnetism (High J_S) Martensitic transformation (rubber like behavior)
Not needed	
Magnetocrystalline anisotropy	Magnetostriction



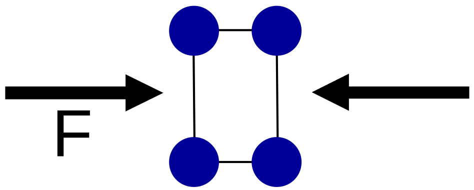


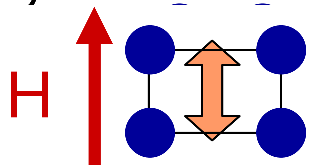
Martensitic and Ferromagnetic

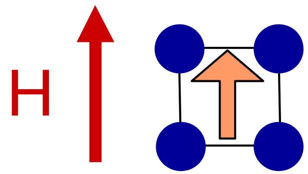
Crystallographic variants

Coupled by magneto-Crystalline anisotropy

Magnetic domains





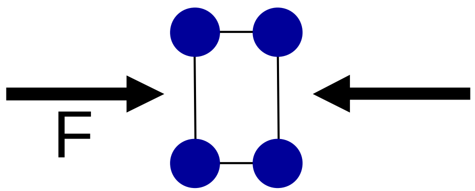


Short axis aligned by stress

Magnetization direction aligned by field

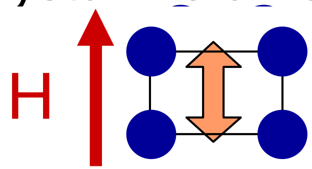
Domain and variant movement
→ local mechanism

Crystallographic variants

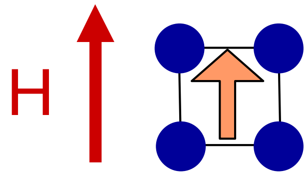


Short axis aligned by stress

Coupled by magneto-crystalline anisotropy

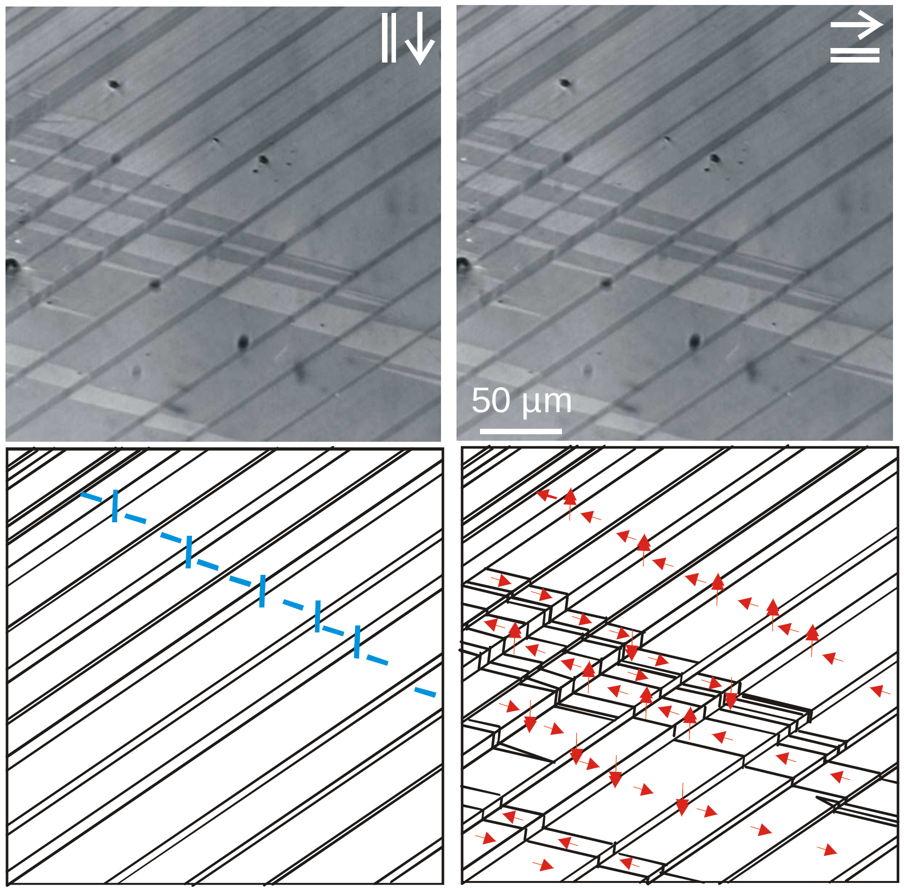


Magnetic domains



Magnetization direction aligned by field

Kerr microscopy:



B1: J. McCord,
R. Schäfer,
IFW Dresden

Twin boundaries
(Variant boundaries,
grain boundaries)

90° and 180°
Domain boundaries

Magnetic Shape Memory Alloys

Magnetically Induced Martensite (MIM)

+ Little constrains on microstructure
+ No magnetocrystalline anisotropy needed

Forces?

- High fields > 1 T
- Works only at the vicinity of martensitic transformation
- Magnetocaloric effect inhibits high frequency

Magnetically Induced Reorientation (MIR)

- Rubber like behavior needed
- High magnetocrystalline anisotropy
- Low forces

+ Moderate fields < 1 T
+ Works below martensitic transformation
+ High frequency (kHz) possible