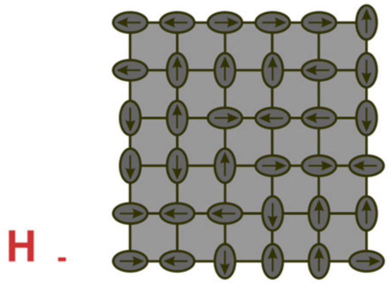
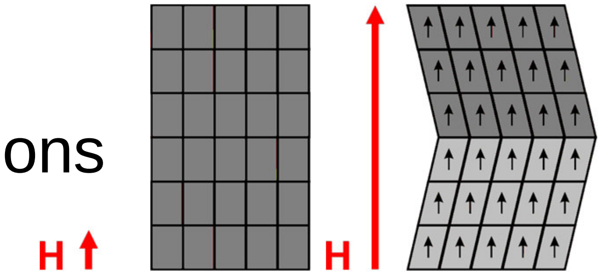
Magnetoelastic Materials

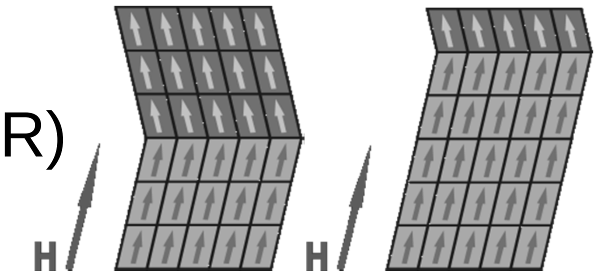
- Magnetostriction



- Magnetically Induced Structural Transitions



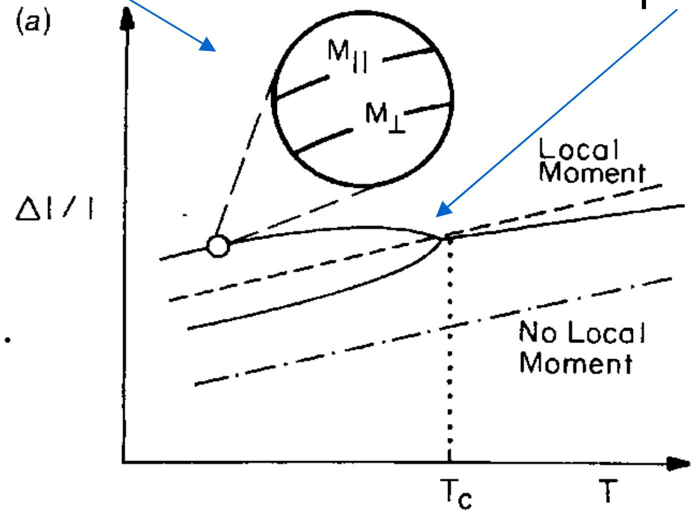
- Magnetically Induced Reorientation (MIR)



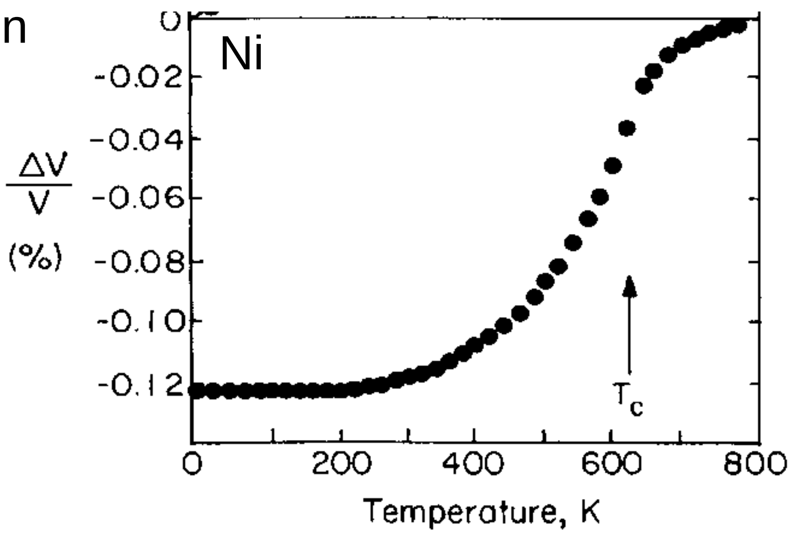
Magnetostrictive effects

Anisotropic magnetostriction

Spontaneous magnetostriction

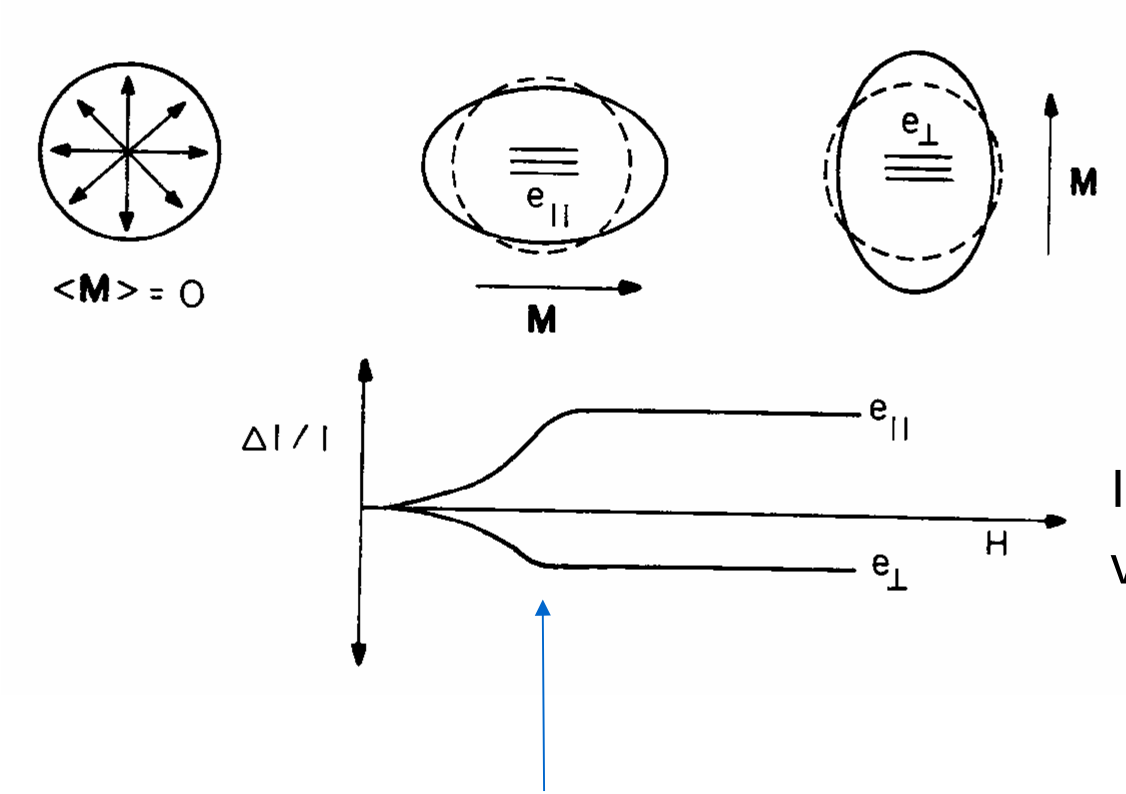


Volume magnetostriction



R. C. O'Handley, Modern Magnetic Materials (2000)

Anisotropic magnetostriction

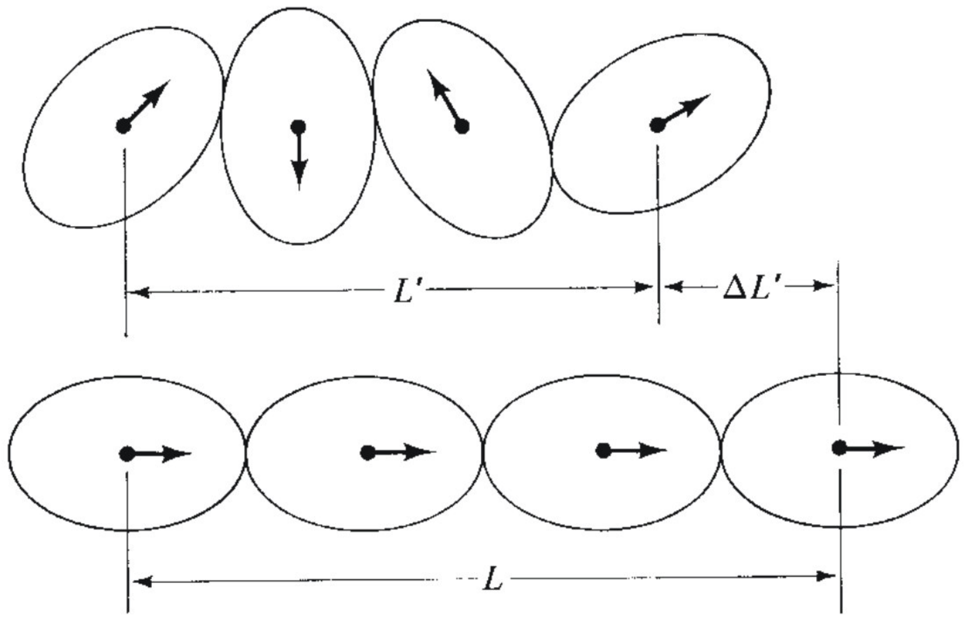


In first order, volume is conserved

Saturation magnetostriction λ_S when all moments are aligned

R. C. O'Handley, Modern Magnetic Materials (2000)

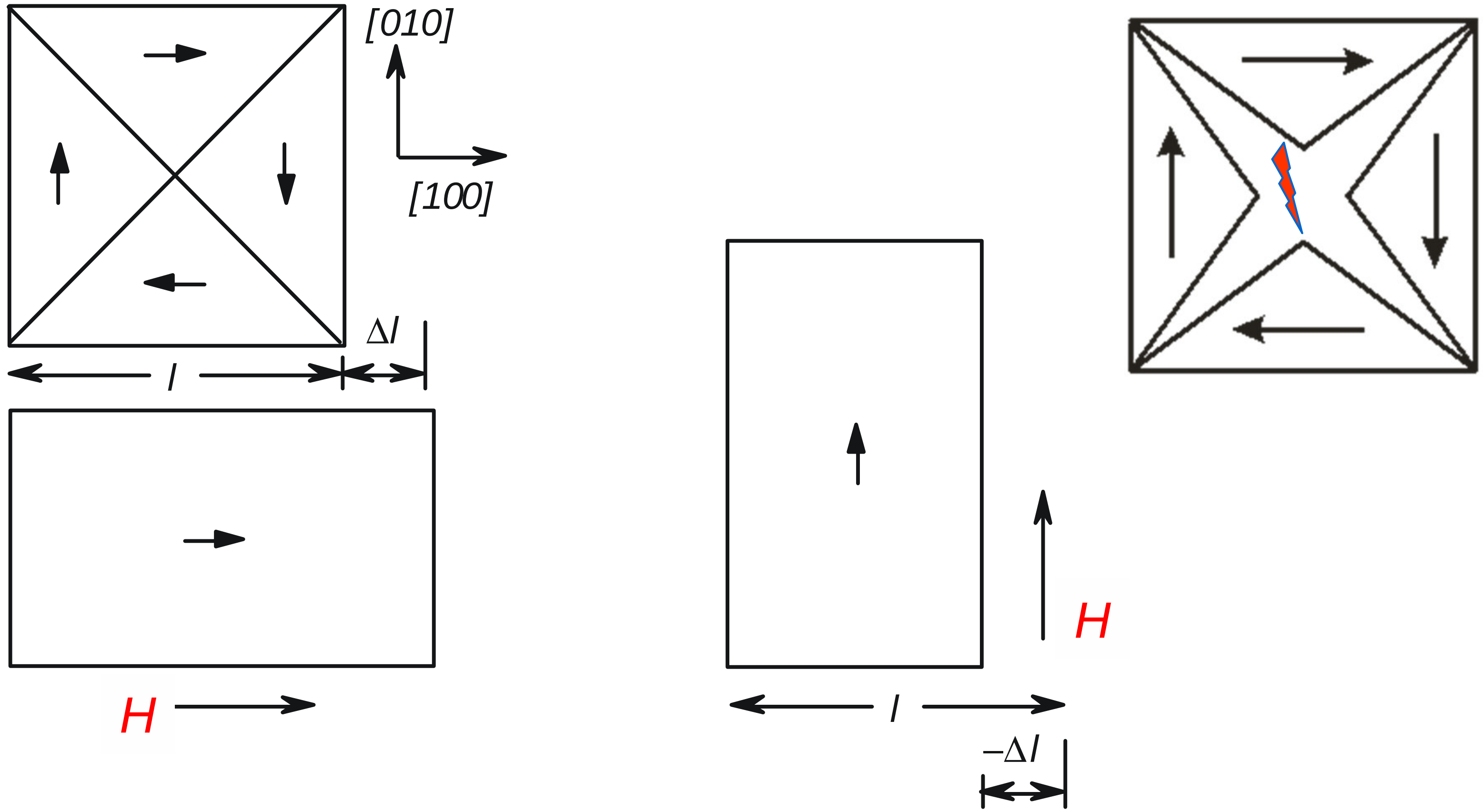
Origin of magnetostriction



Below T_C:
Spin-Orbit coupling alligns orbits
Modifies distance between atoms (spontaneous magnetostriction)
Magnetic field modifies direction (anisotropic magnetostriction)

B. D. Cullity, Introduction to Magnetic Materials (1972)

Magnetostriction and domains



- Ideal case:

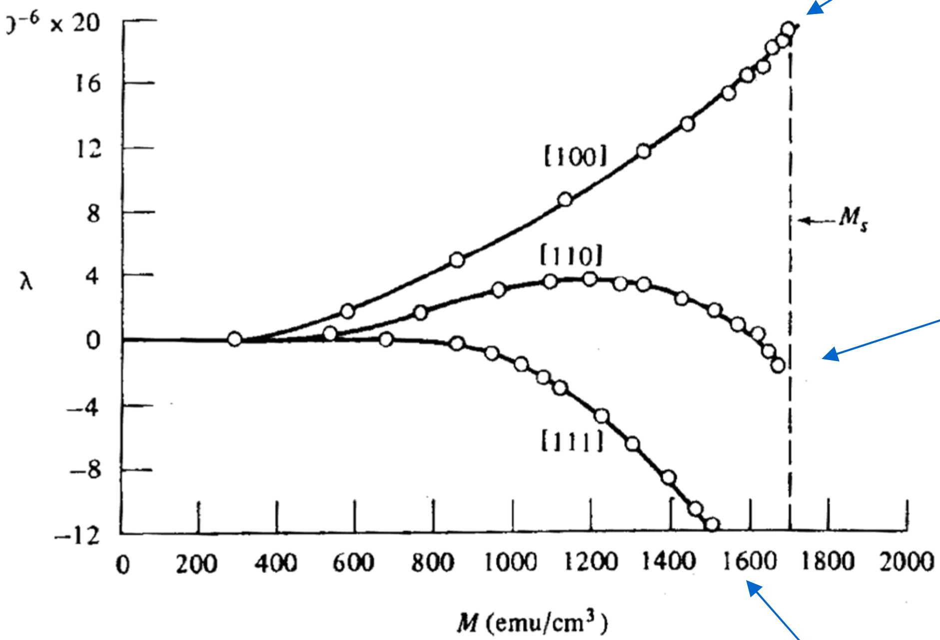
  Demagnetized state consists of all possible domains in equal fraction

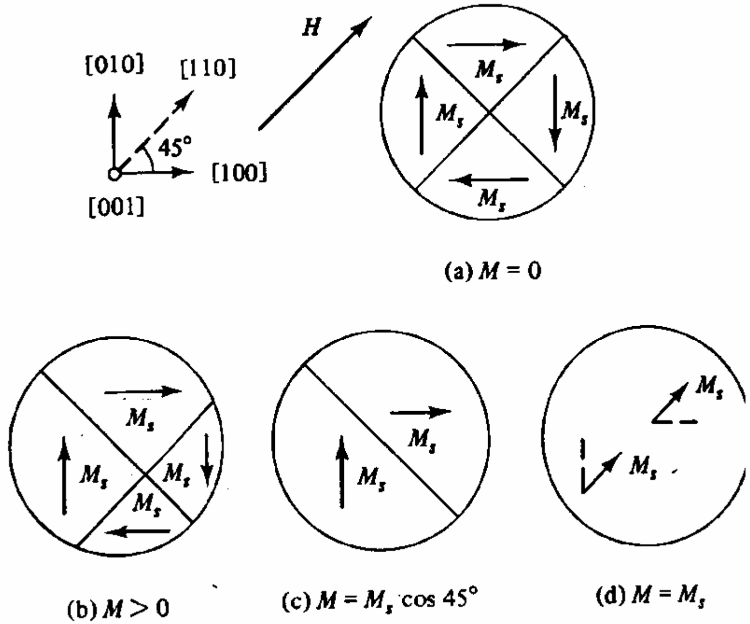
  $\lambda_S > 0$: Extension in field direction

  $\lambda_S < 0$: Compression in field direction

Magnetostriction of a Fe single crystal

$\lambda_{100} = +20.5\text{x}10^{-6}$, easy axis





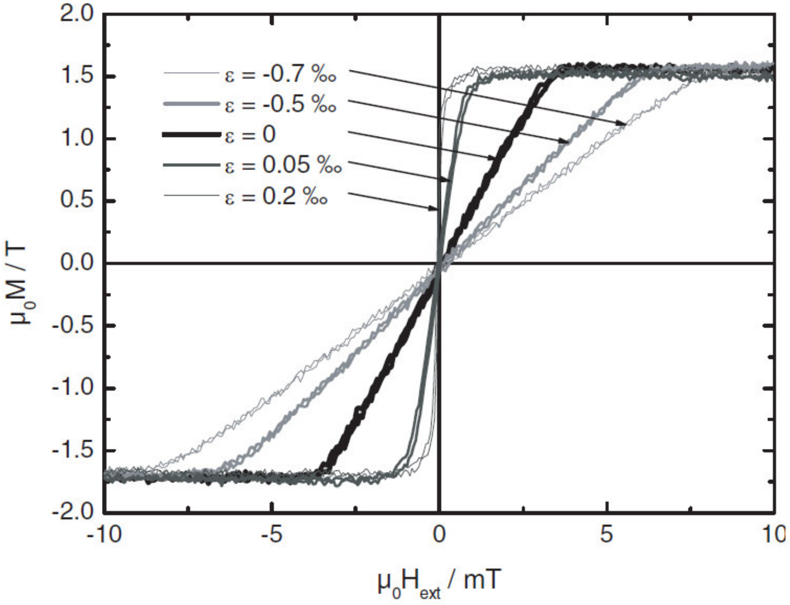
$\lambda_{111} = -21.5\text{x}10^{-6}$, hard axis

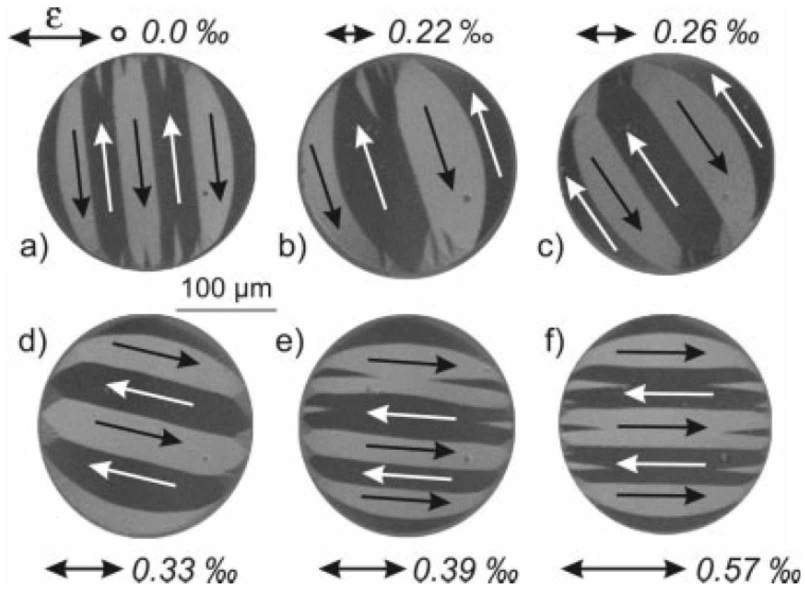
- Complex behavior when domain wall motion and rotation is involved

B. D. Cullity, Introduction to Magnetic Materials (1972)

Inverse magnetostriction

Straining of a 500 nm FeCoBSi film



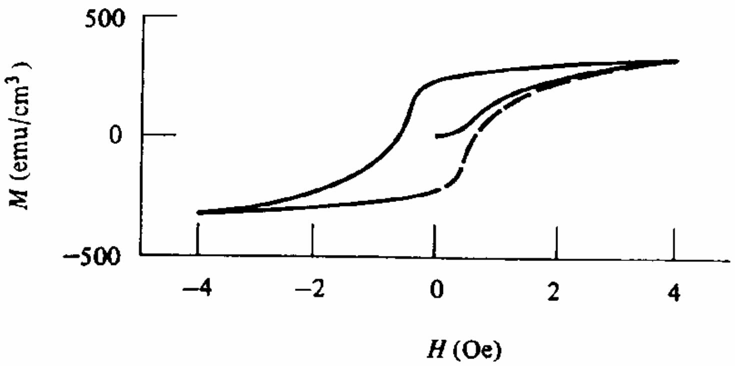


- Stress induced anisotropy
- Easy axis aligns along strain direction

S. Glasmachers, M. Frommberger, J. McCord, E. Quandt, phys. stat. sol. (a) 201, 3319 (2004)

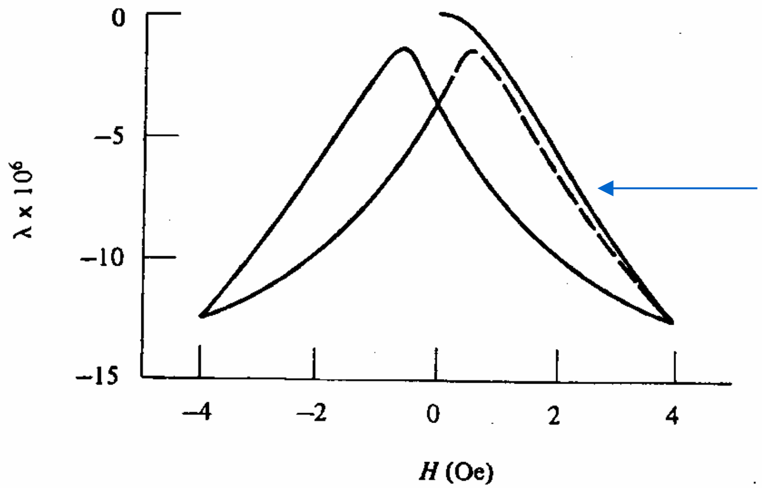
Applications of magnetostriction

Ni



Applications:

- Ultrasonic sound generators
- Microactuators + sensors



Symmetric curve

-> Frequency doubled

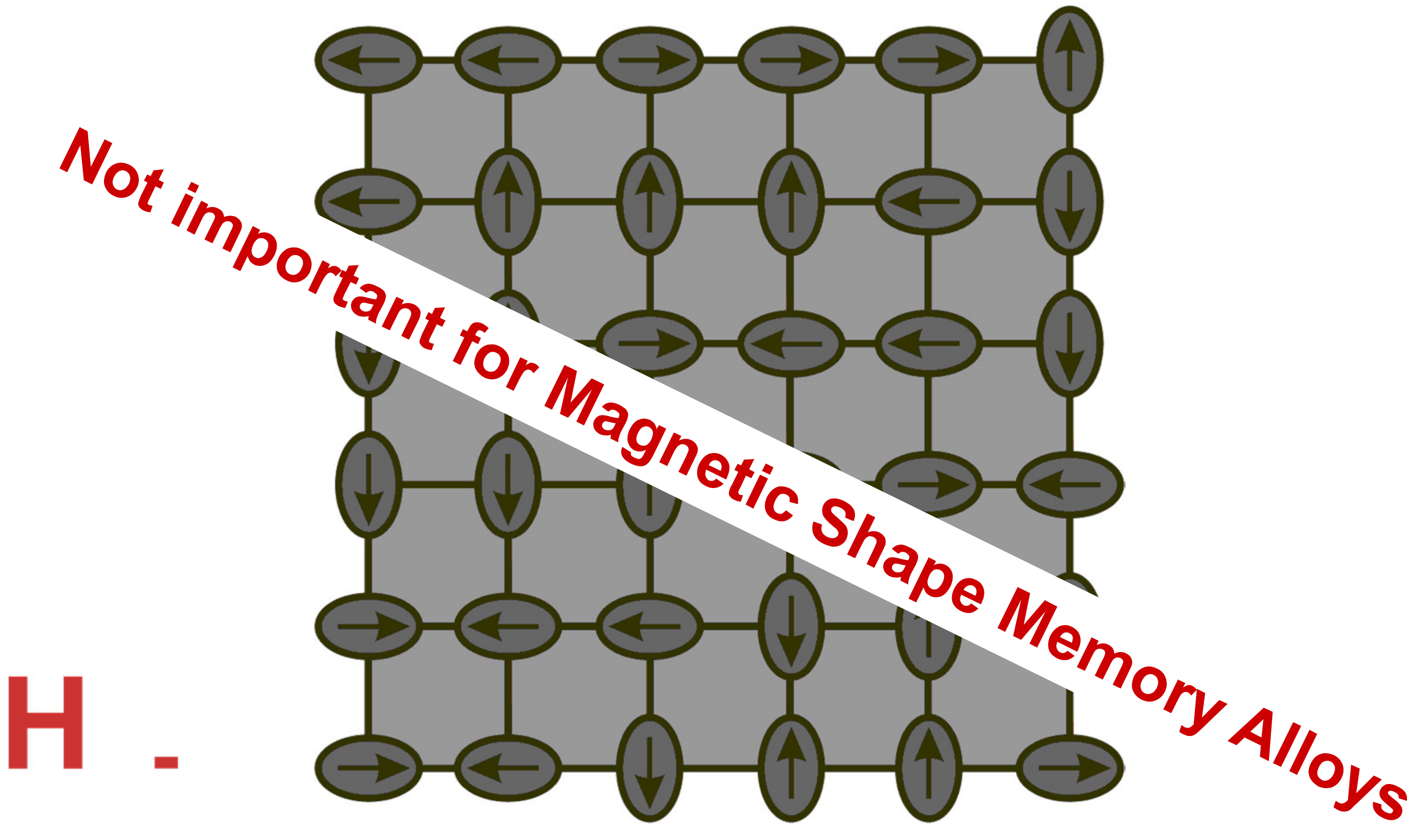
Best for applications:

- Low hysteresis
- Bias field

Best materials:

- Terfenol-D $(Dy,Tb)Fe_2$: 0.24%
- Galfenol (Fe-Ga): 0.03 %

Anisotropic magnetostriction



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

- *Single ion anisotropy*

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

Martensitic transformation

$T > T_M$:

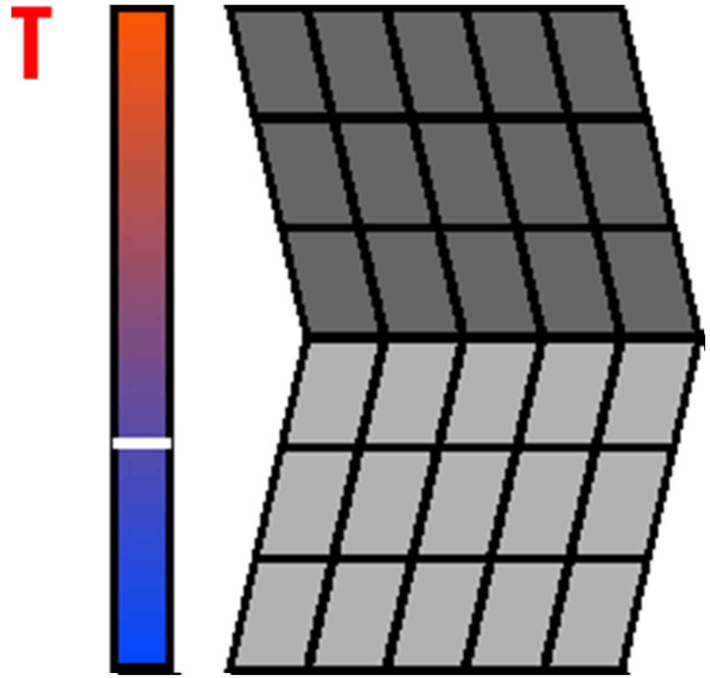
Austenite

(high symmetry)

$T < T_M$:

Martensite

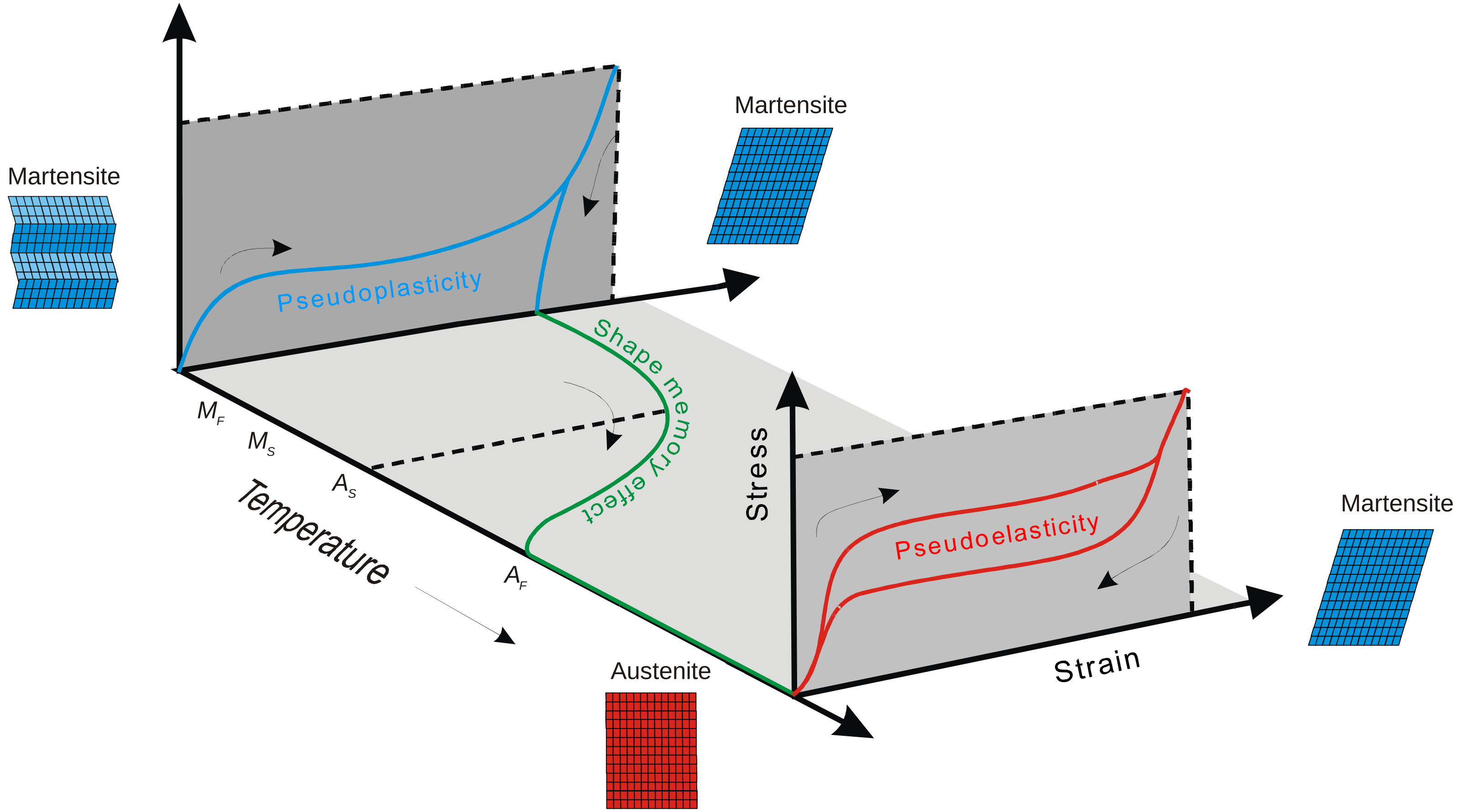
(low symmetry)



- No diffusion, reversible
- Twinned microstructure

+	Strain > 5%
+	High forces
-	Low frequency

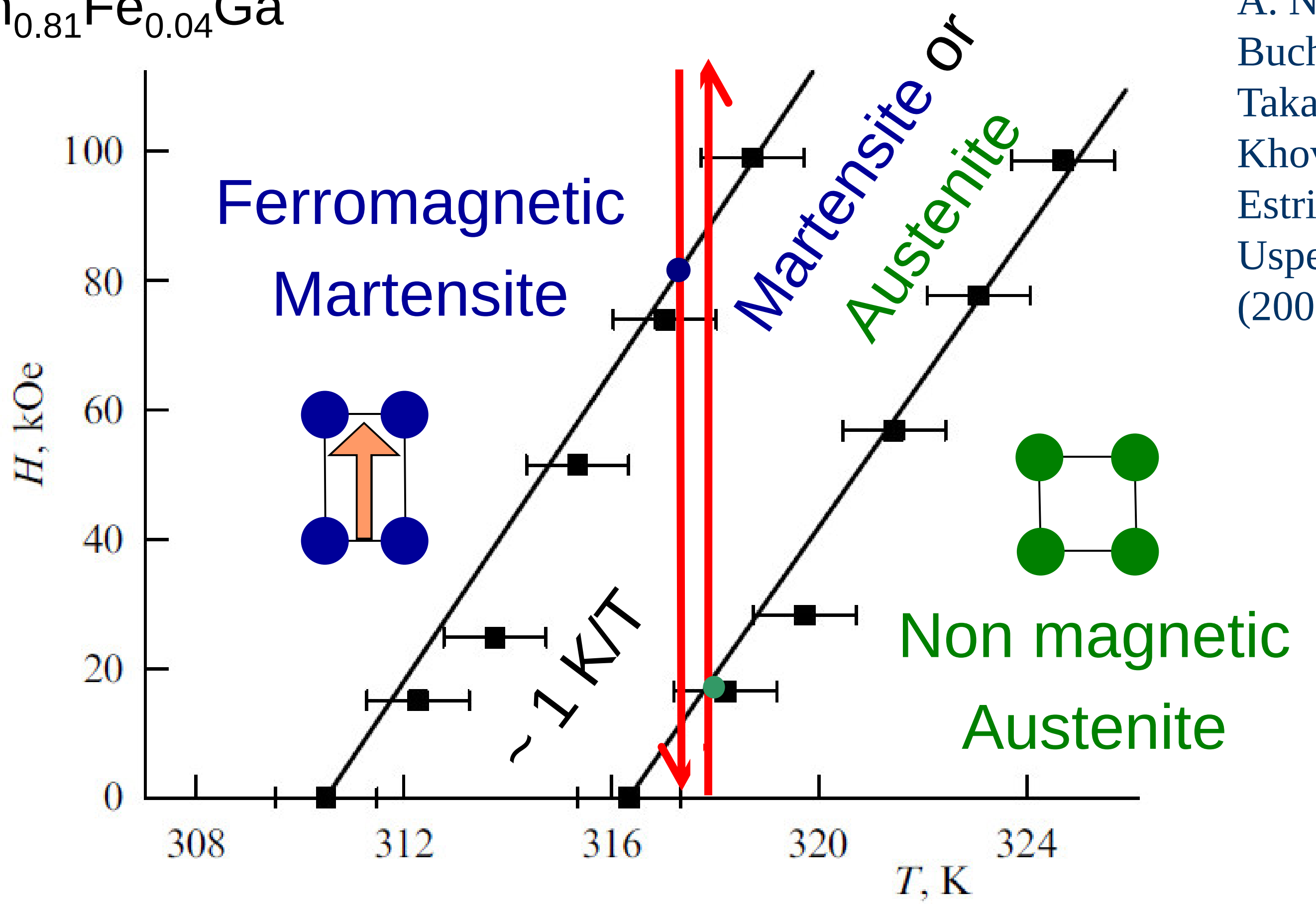
Stress – Strain - Temperature



- Different trajectories can be used in shape memory materials
  - Pseudoelasticity
  - Pseudoplasticity
  - Shape memory effect

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

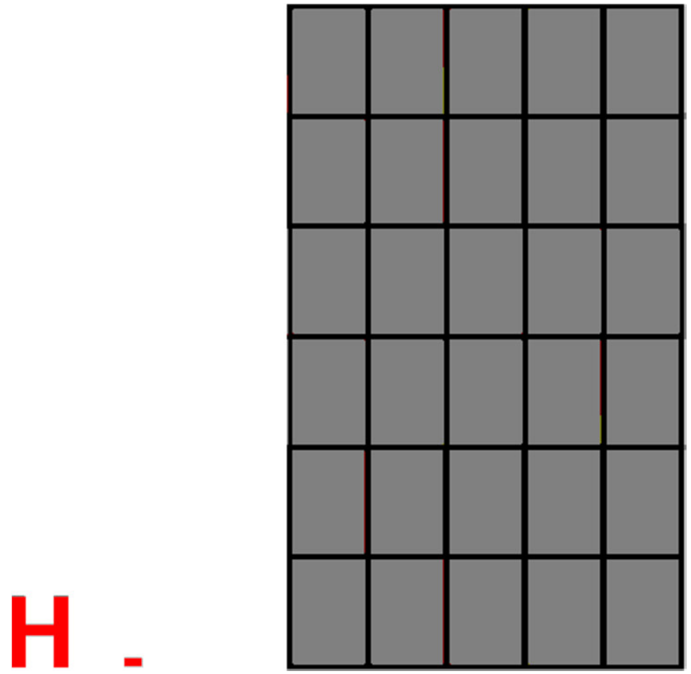
Magnetically Induced Martensite (MIM)

MSM

Magnetic field favors ferromagnetic phase

Clausius Clapeyron:

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



- Magnetic actuation
- First order structural transition
- Latent heat

+ Remote actuation

Electronic origin of martensitic transformation

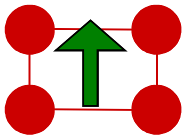
Ni_2MnGa

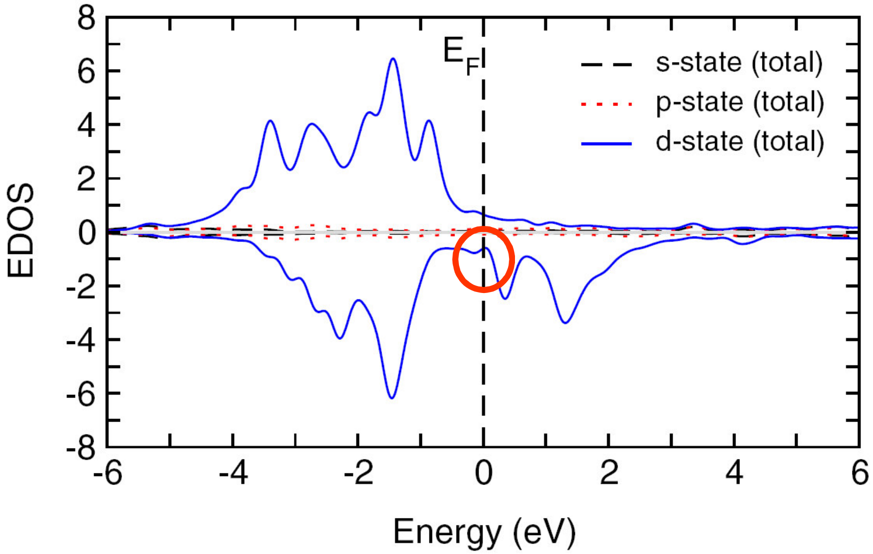
M. Gruner

A3: P. Entel,
U. Duisburg-Essen

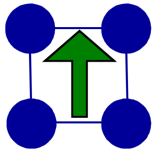
UNIVERSITÄT DUISBURG ESSEN

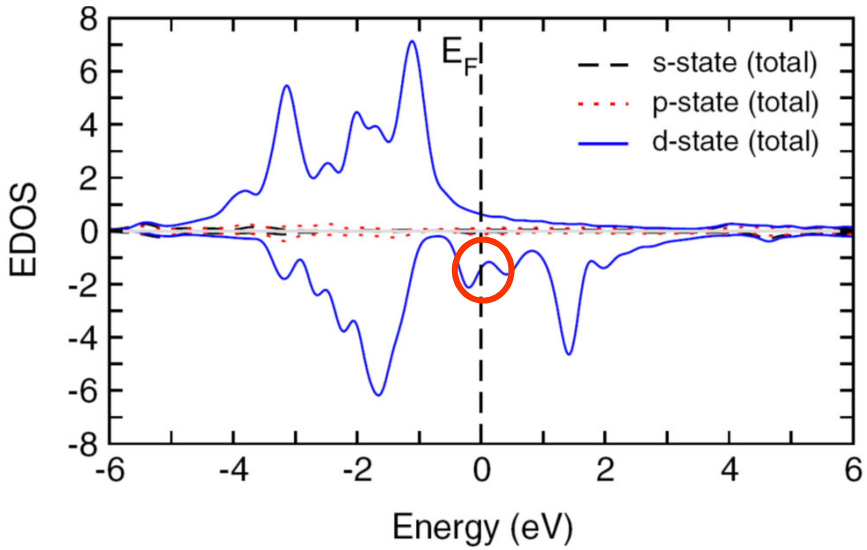
Martensite





Austenite



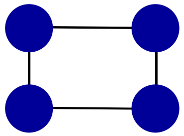


- Austenite and Martensite are ferromagnetic
- Martensitic deformation allows to reduce energetically unfavorable high DOS at E_F

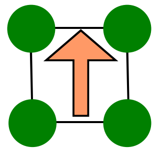
P. Entel et al. J. Phys. D: Appl. Phys. 39 (2006) 865

Metamagnetic martensite

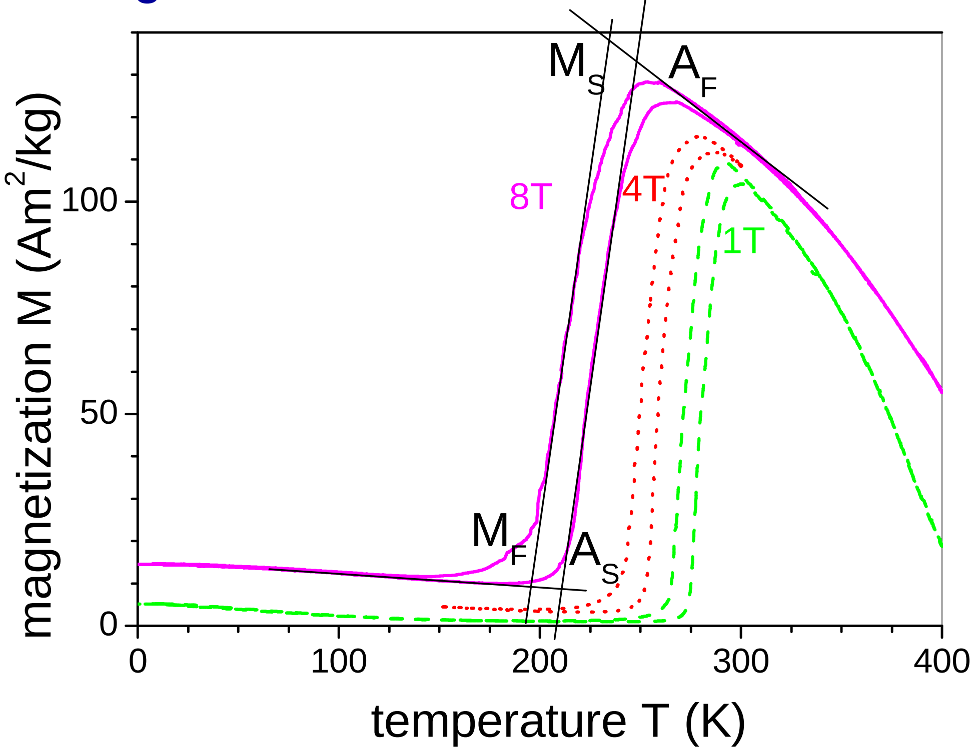
$Ni_{45}Co_5Mn_{36.7}In_{13.3}$



Nonmagnetic Martensite



Ferromagnetic Austenite



- Collapse of magnetisation by martensitic transition
- External field shifts martensitic transformation to lower temperatures

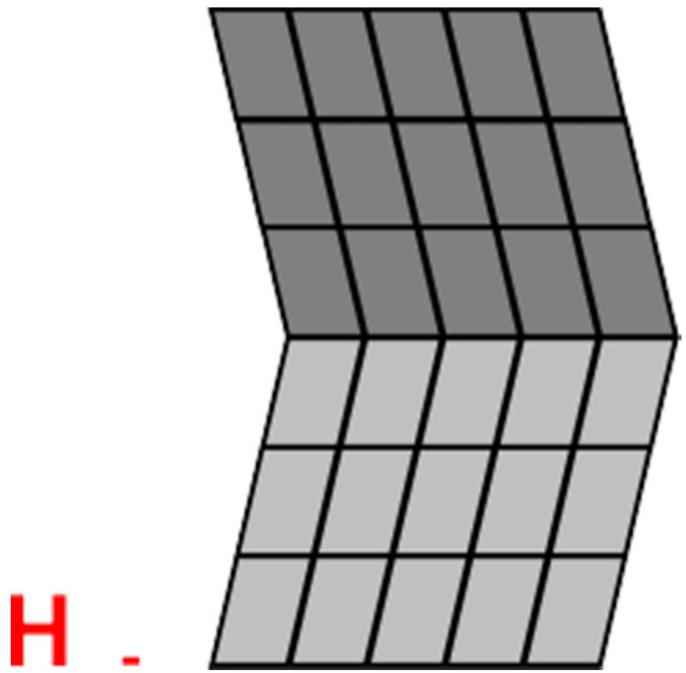
A.N. Vasiliev, O. Heczko, O.S. Volkova, T.N. Vasilchikova, T.N. Voloshok, K.V. Klimov, W. Ito, R. Kainuma, K. Ishida, K. Oikawa, and S. Fähler, J. Phys. D: Appl. Phys. 43 (2010) 055004

Magnetically Induced Austenite (MIA)

Magnetic field favors
ferromagnetic phase

Clausius Clapeyron:

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



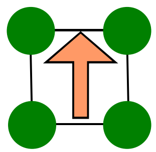
Negative $\Delta J \rightarrow H$ stabilizes austenite

Larger ΔJ *by metamagnetic transition* (not close to T_C)

$\rightarrow$ Lower magnetic field required

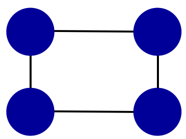
Magnetically Induced Austenite (MIA)

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



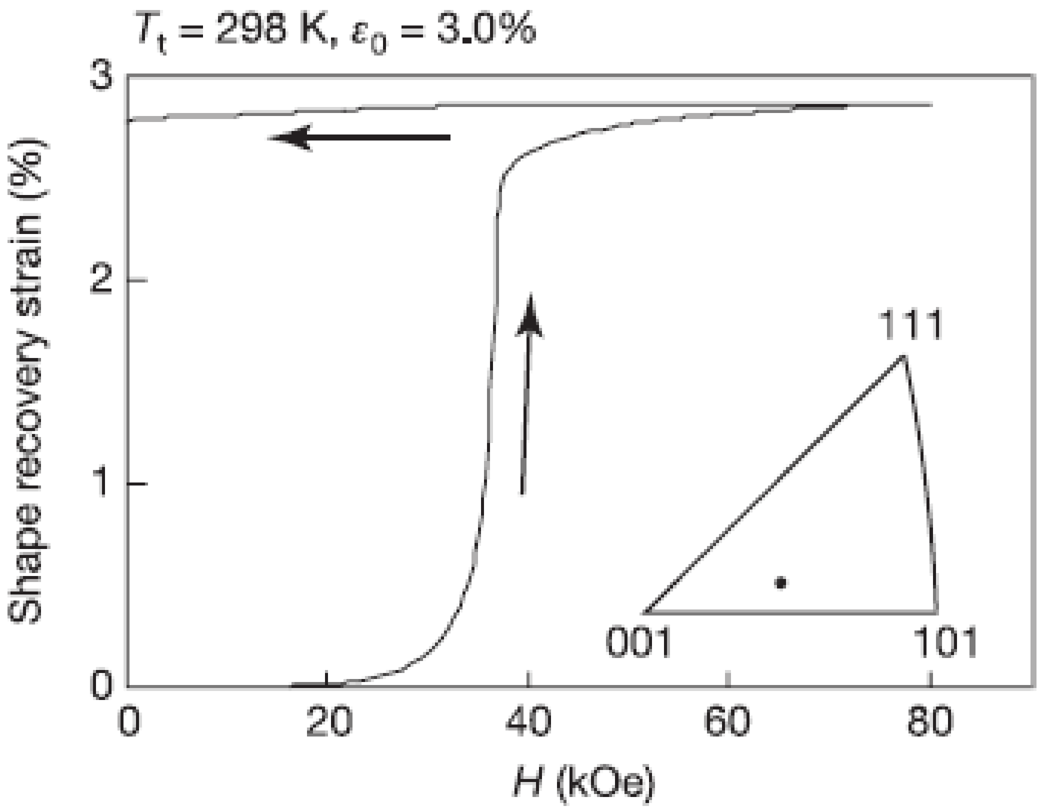
High *J*

Austenite



Low *J*

Martensite

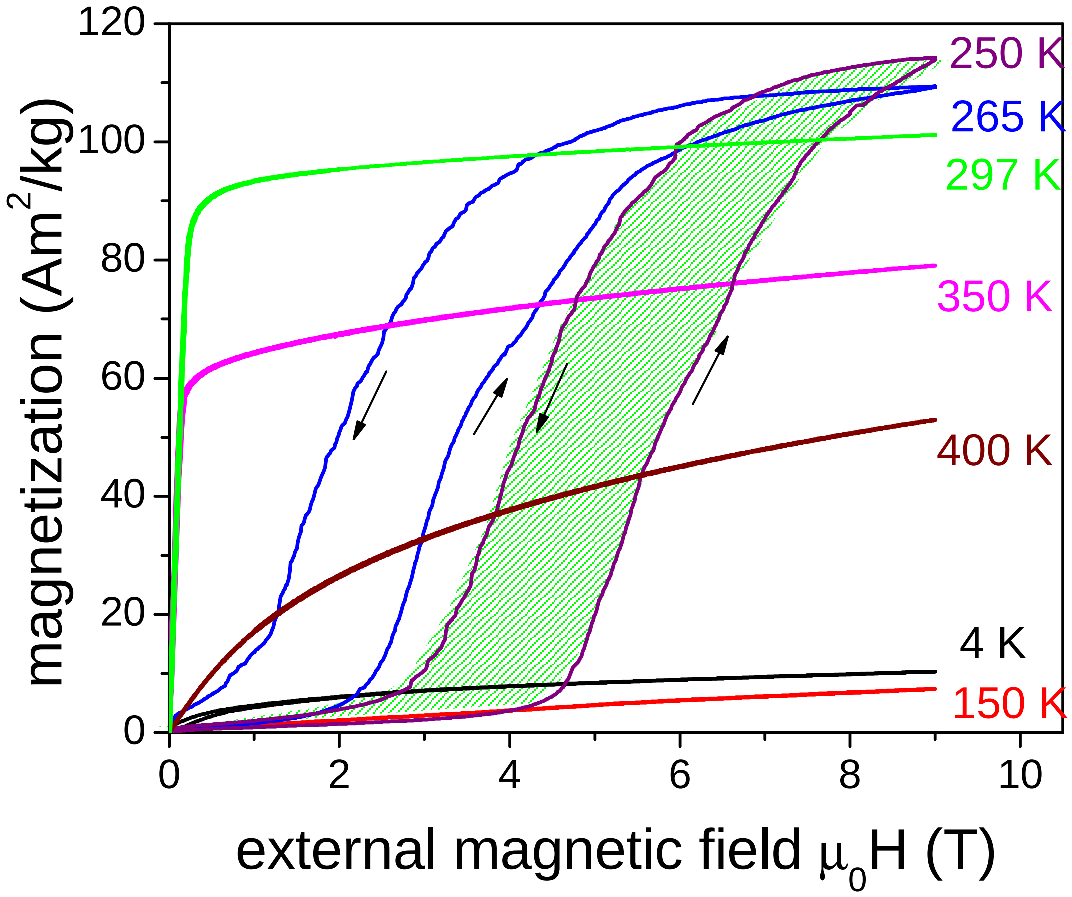


R. Kainuma et al.
Nature 439 (2006) 957

- Hysteresis may inhibit reversibility

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

Energy Balance for MIA



A.N. Vasiliev, O. Heczko, O.S. Volkova, T.N. Vasilchikova, T.N. Voloshok, K.V. Klimov, W. Ito, R. Kainuma, K. Ishida, K. Oikawa, and S. Fähler, J. Phys. D: Appl. Phys. 43 (2010) 055004

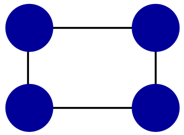
- Energy input: $\int_0^{H_S} \Delta J dH$ (hatched area)
- Can be increased by inceasing H
- But: In this case no external work was performed, hence Energy input = Hysteresis loss

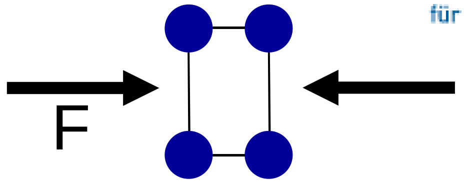
Rubber-like behavior

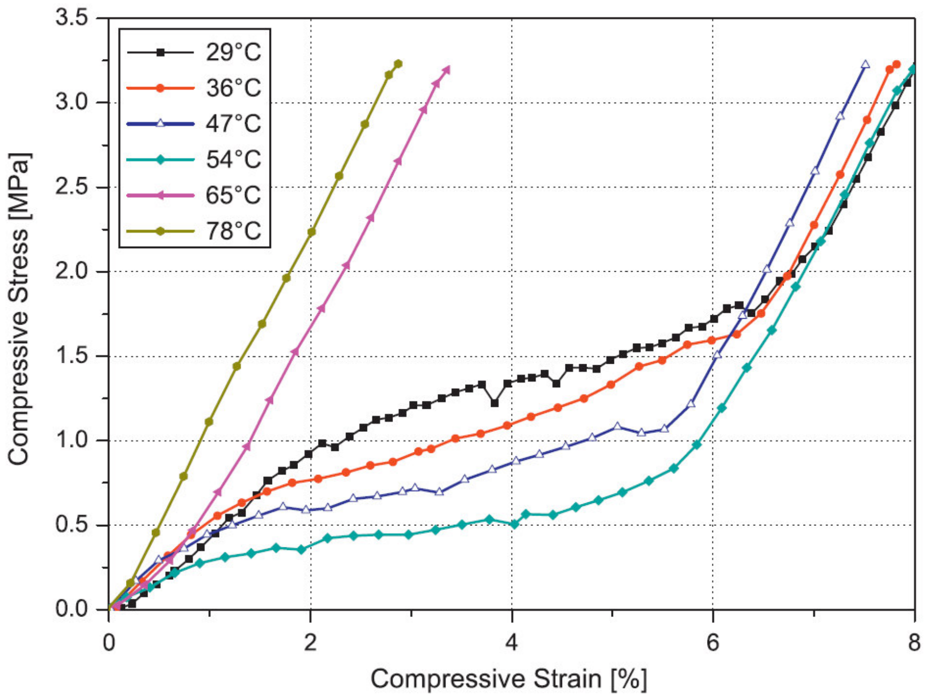
Ni-Mn-Ga K. Rolfs, A. Mecklenburg | B2: R. Schneider

5M

At const T < T_M







- Easy movement of twin boundaries (~ MPa)

- Little pinning of twin boundaries at defects

K. Rolfs, A. Mecklenburg, J.-M. Guldbakke, R.C. Wimpory, A. Raatz, J. Hesselbach, R. Schneider, JMMM 321 (2009) 1063

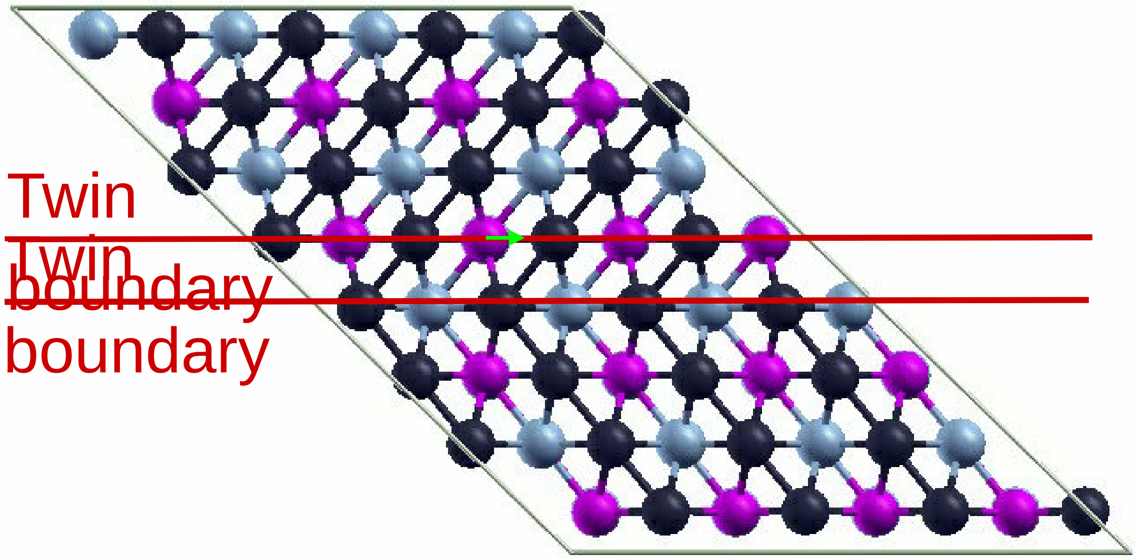
Twin boundary movement

NM Ni-Mn-Ga

M. Gruner

A3: P. Entel,
U. Duisburg-Essen

UNIVERSITÄT DUISBURG ESSEN

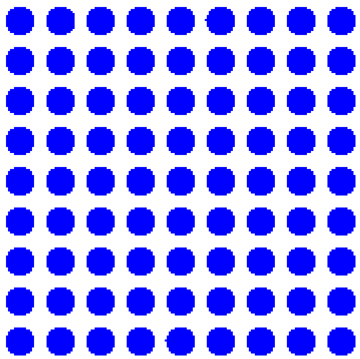


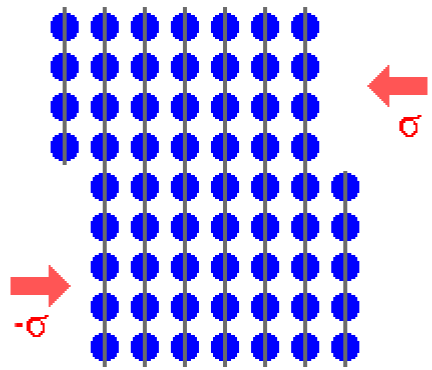
- Only small movements of atoms required
- But a collective movement would require to move 10^{23} atoms simultaneously...

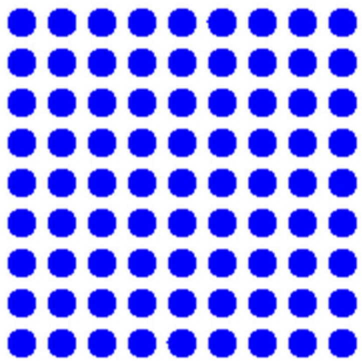
 M. E. Gruner, P. Entel, I. Opahle, M. Richter, J. Mat. Sci. 43 (2008) 3825

Excursion: Dislocations

- How to deform a crystals by external stress?







H. Föll/ U. Kiel

http://www.tf.uni-kiel.de/

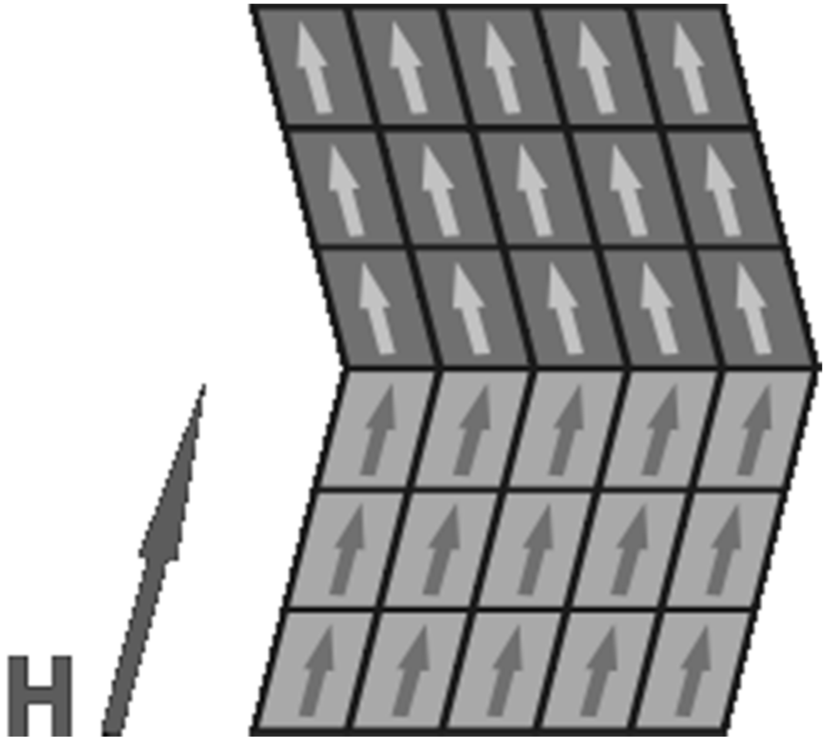
matwis/amat/def_en/index.html

- Dislocations allows to move line defect instead of a complete plane

Magnetically Induced Reorientation (MIR)

Twin boundary movement

No phase transition,
affects only microstructure

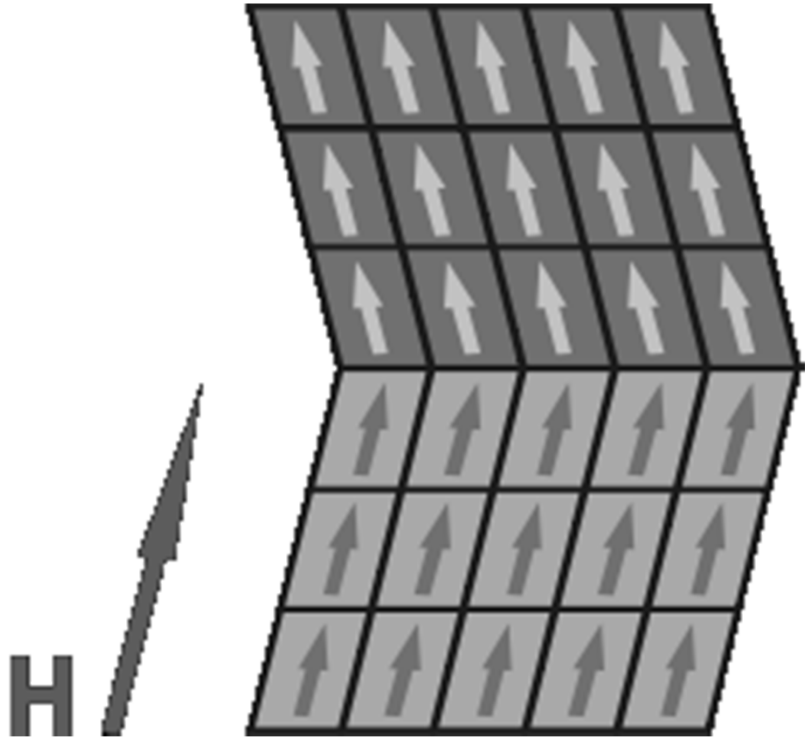


Requires:

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

++ Strain up to 12 %
+ High frequency

Ferromagnet



- Rotation of magnetization must be avoided

  ⇒ high magnetocrystalline anisotropy needed

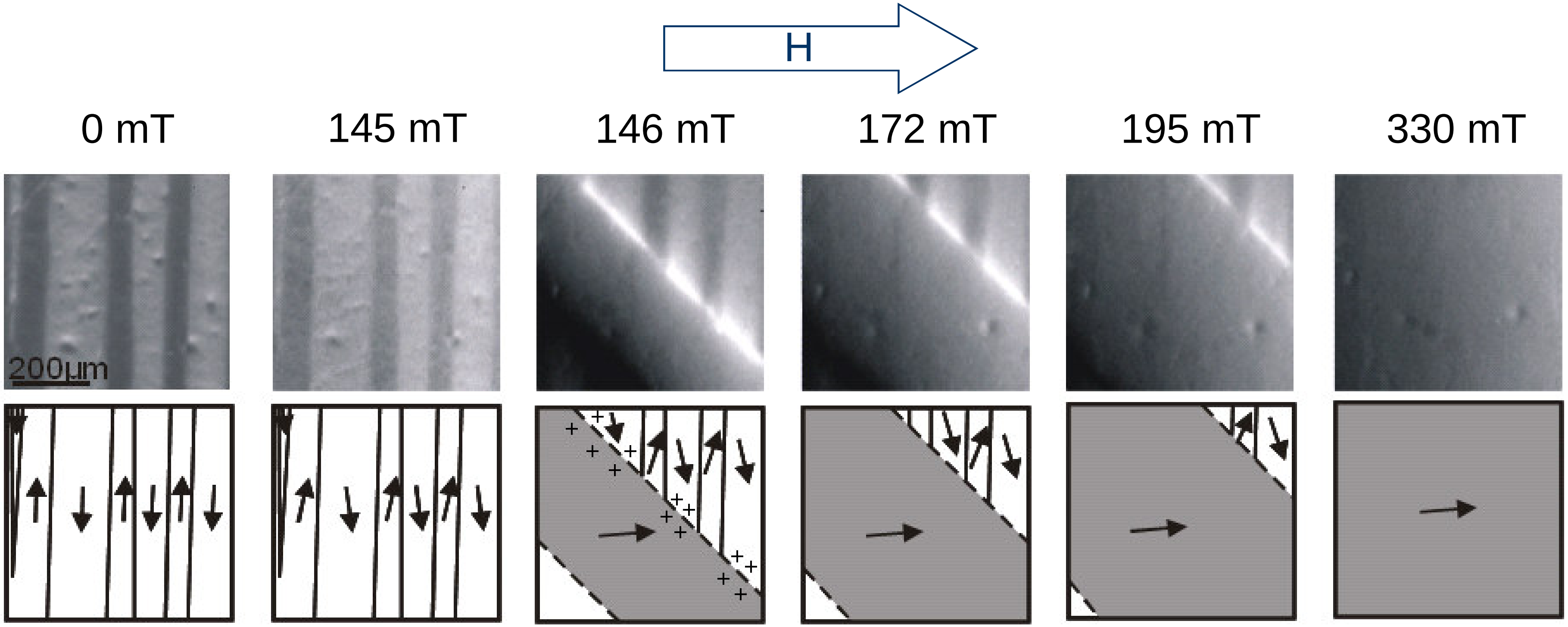
- High H_A
- Switching field $H_S < H_A$

Domain pattern during MIR

5M Ni-Mn-Ga

Y. W. Lai

B1: J. McCord, R. Schäfer
IFW Dresden



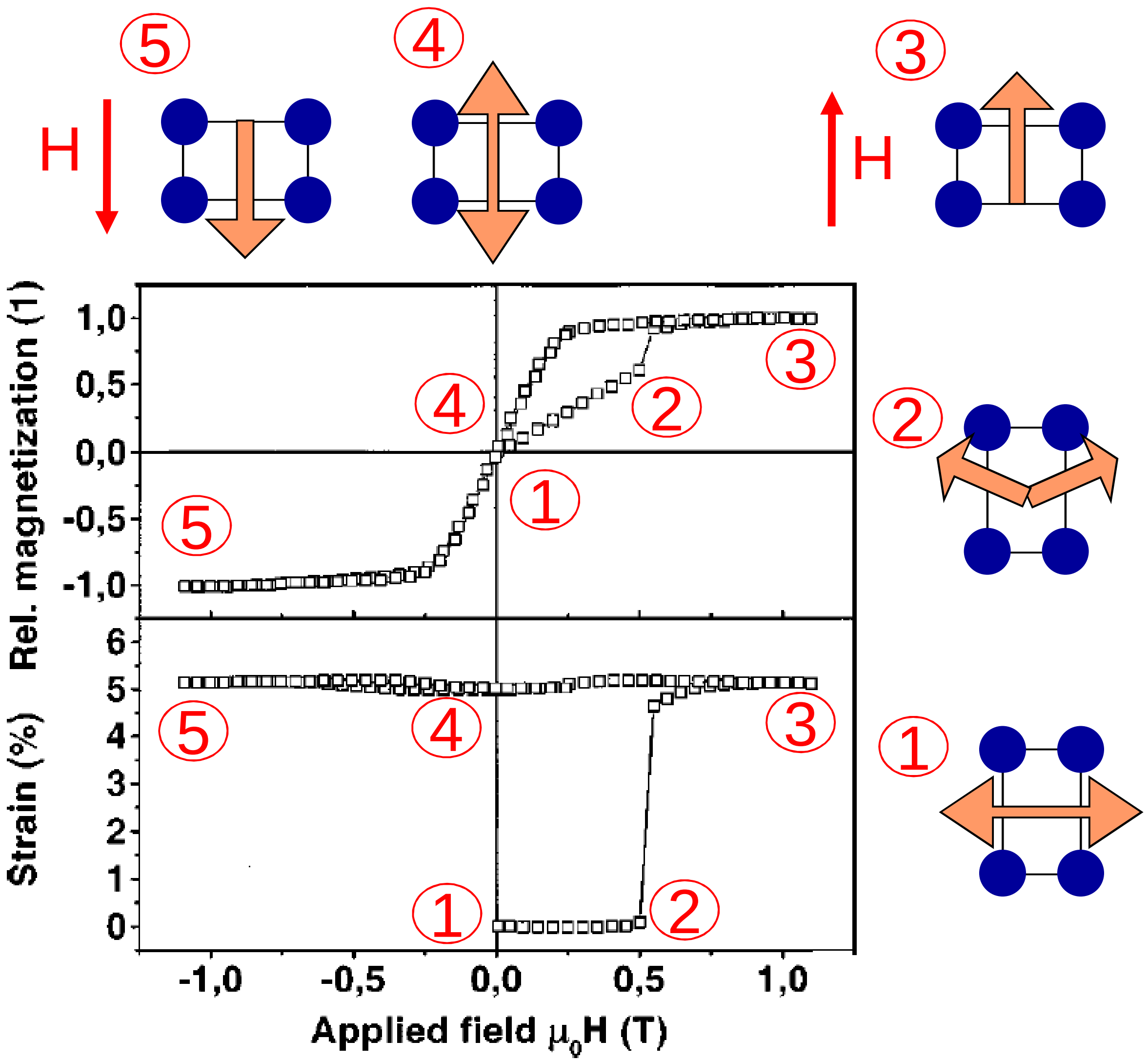
- Magnetic field moves twin boundary instead of rotating magnetization

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

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

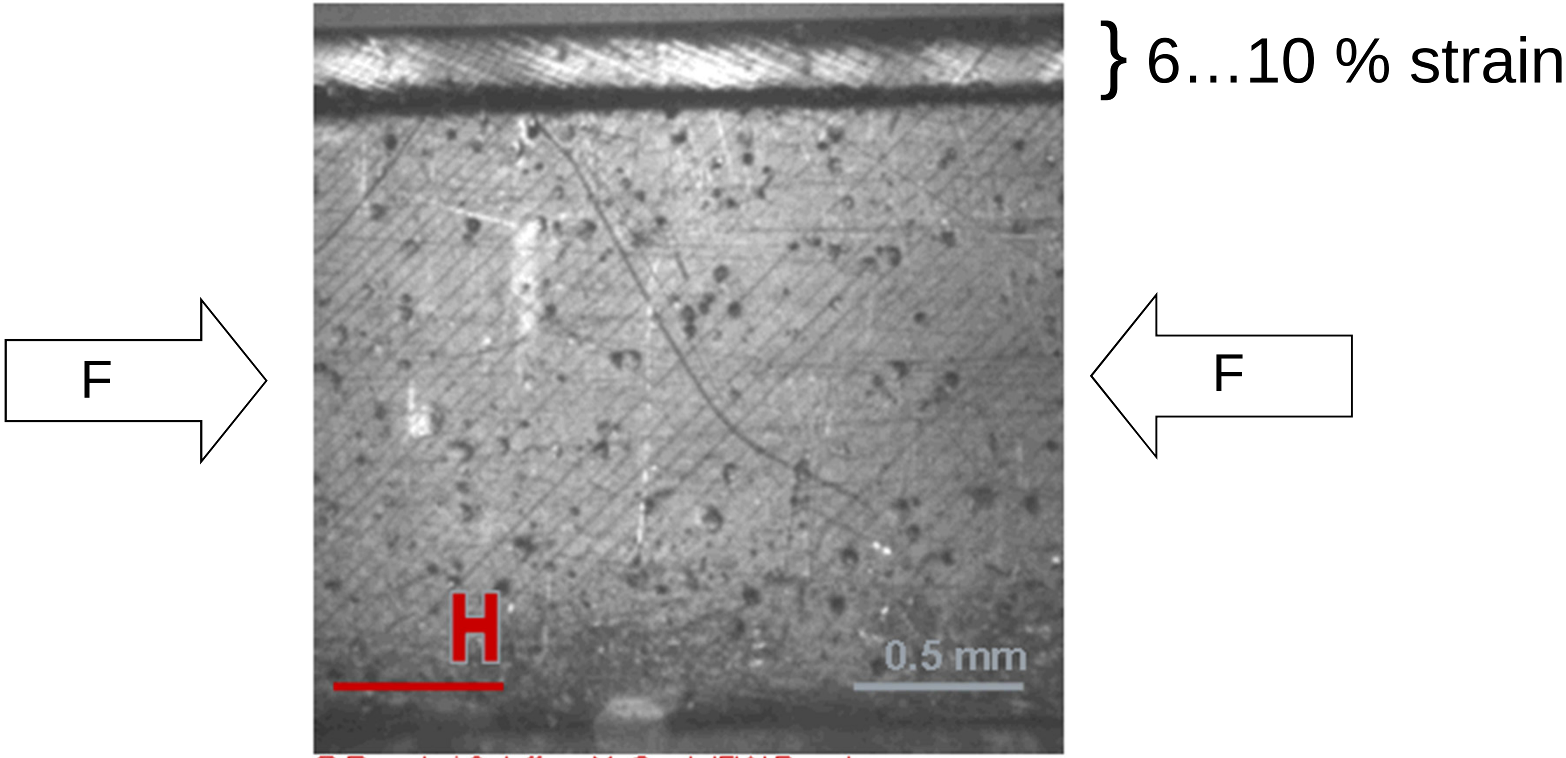
- moderate switching field $H_S < 1$ T

Magnetically Induced Reorientation

5M Ni-Mn-Ga

Y. W. Lai

B1: J. McCord, R. Schäfer
IFW Dresden

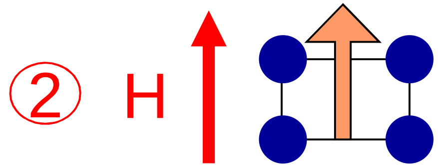


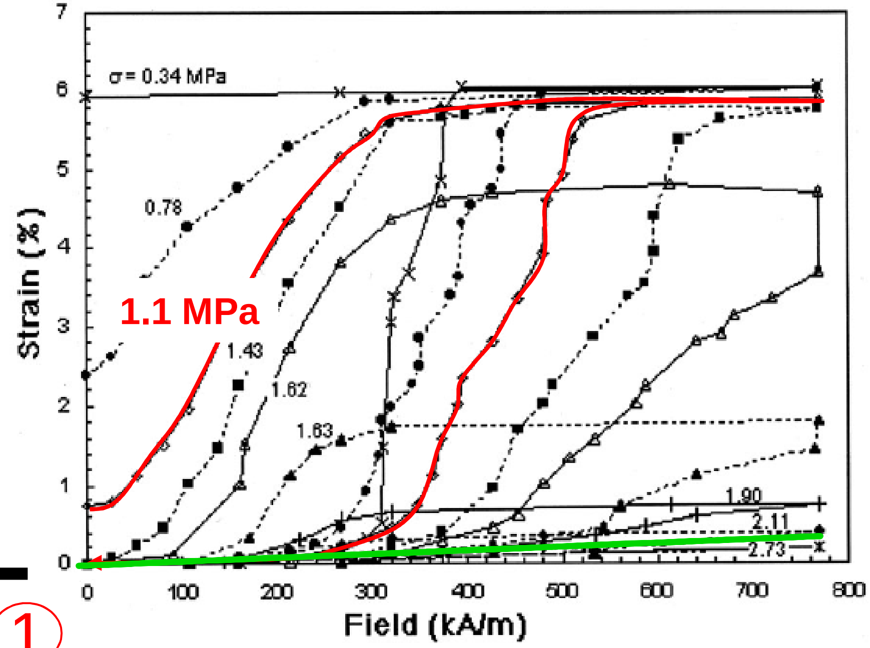
Restoring force by spring

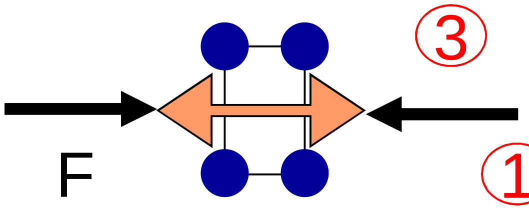
Actuation under load

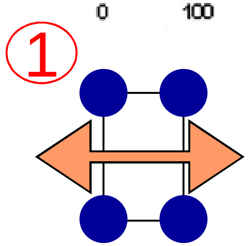
Ni-Mn-Ga

5M









Blocking stress ~2 MPa

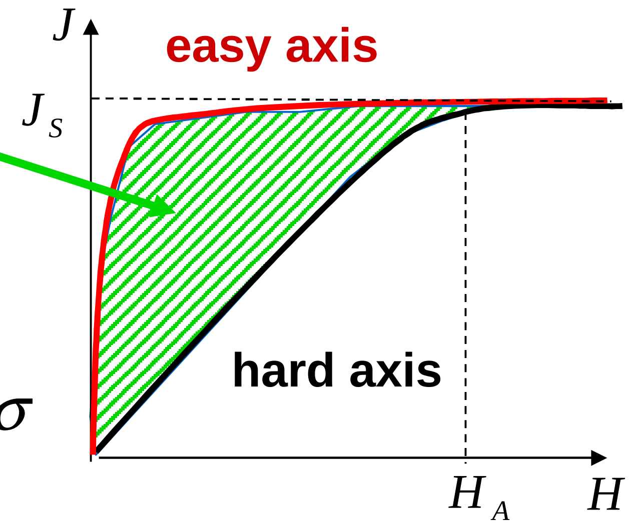
S. J. Murray, M. Marioni, S. M. Allen, R. C. O'Handley, T. A. Lograsso, Appl. Phys. Lett. 77(6) (2000) 886

- low blocking stress
- low forces

Energy balance

Gain of magnetic energy density by reorientation

$$w_{max} = k_U \left(\cong \frac{1}{2} H_A J_S \right)$$



Mechanical work density $w = \sigma \varepsilon_0$

Maximum internal and external stress : σ

Maximum strain : $\varepsilon_0 = 1 - \frac{c}{a} \approx 6...10\%$

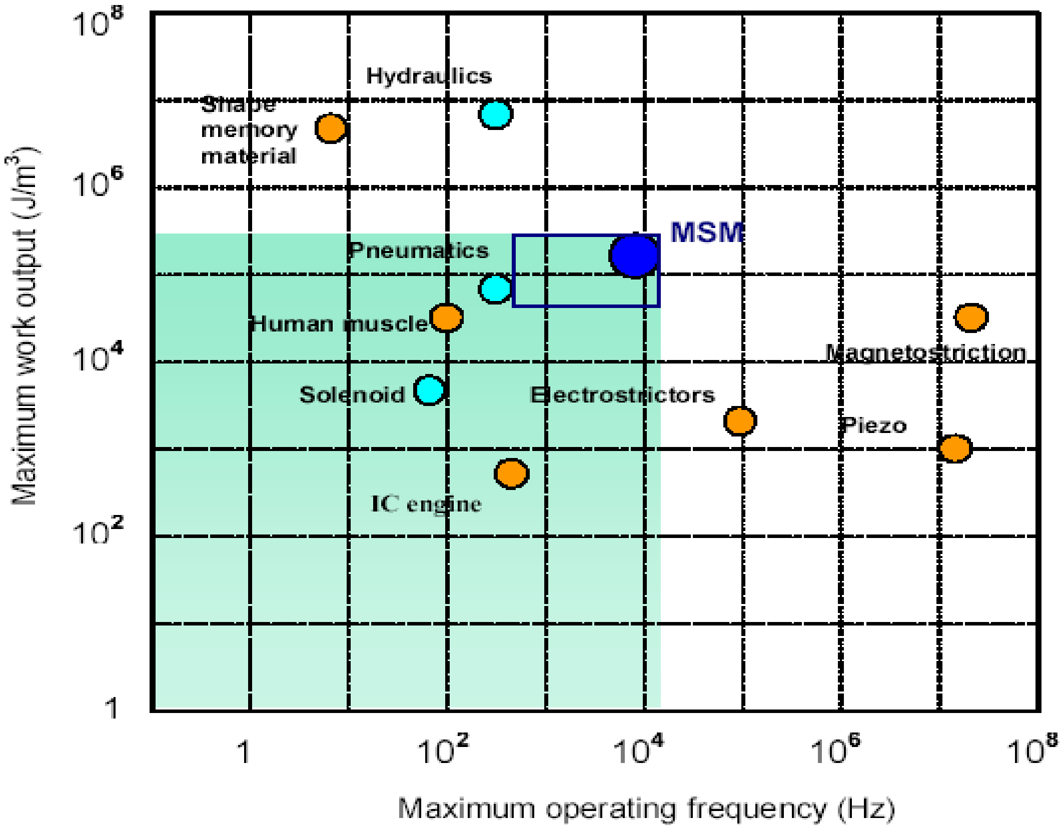
Balance

$$\sigma \varepsilon_0 = k_U$$

$$\Rightarrow \sigma = \frac{k_U}{\varepsilon_0} \approx 2 \text{ MPa}$$

- low blocking stress
- low forces
+ high work output

Comparison with other smart materials



www.intellimat.com

- Strain up to 10%
- High frequency possible
- High specific work output
- Low forces ~ MPa
- Switching fields 0.1 - 1 T

Refers only to the material, not to the complete system!

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 $\Rightarrow$ efficient coupling to external field
- 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

Magnetic Shape Memory Alloys

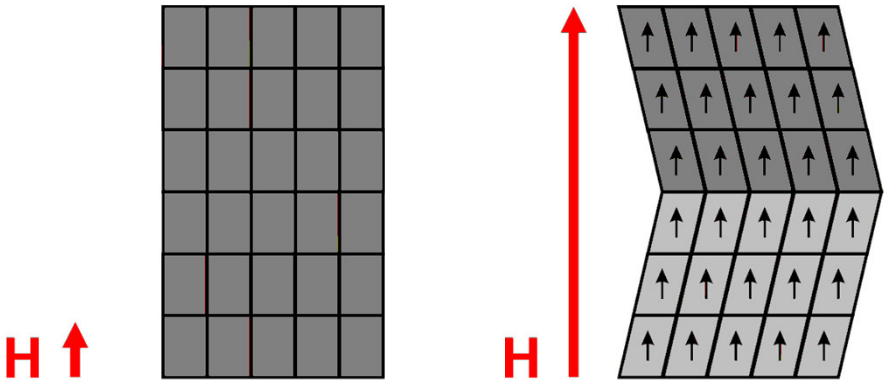
MSM

Magnetically Induced Martensite/Austenite (MIM/MIA)

+ Little constrains on microstructure
+ No magnetocrystalline anisotropy needed

Work input increases with H

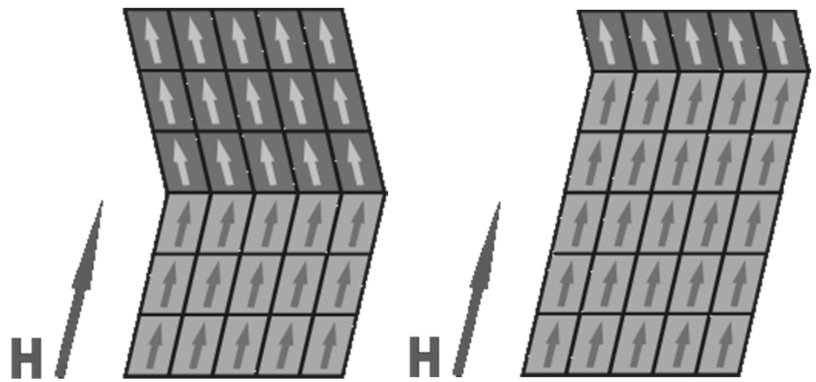
- High fields > 1 T
- Works only at the vicinity of martensitic transformation
- Magnetocaloric effect inhibits high frequency



Magnetically Induced Reorientation (MIR)

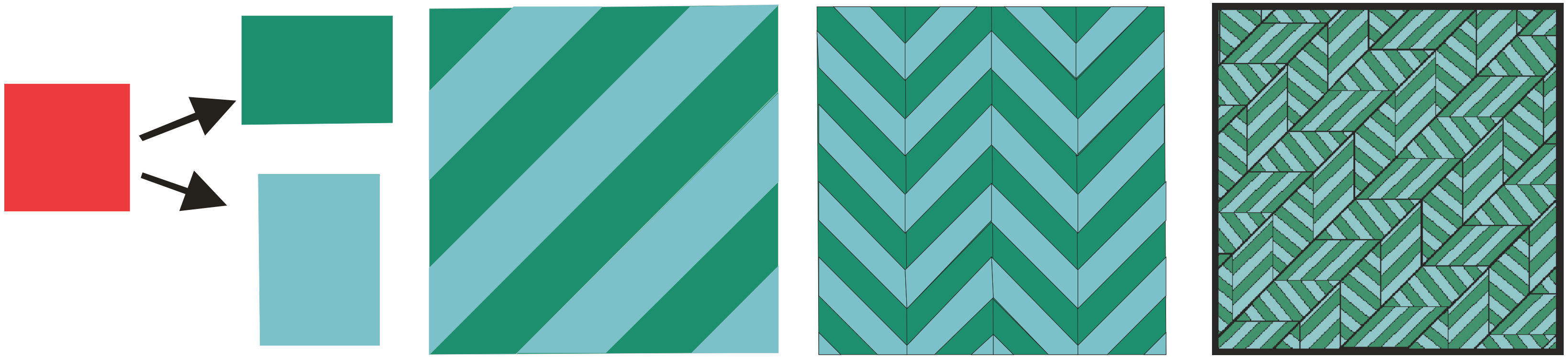
- Rubber like behavior needed
- High magnetocrystalline anisotropy
- Low forces

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

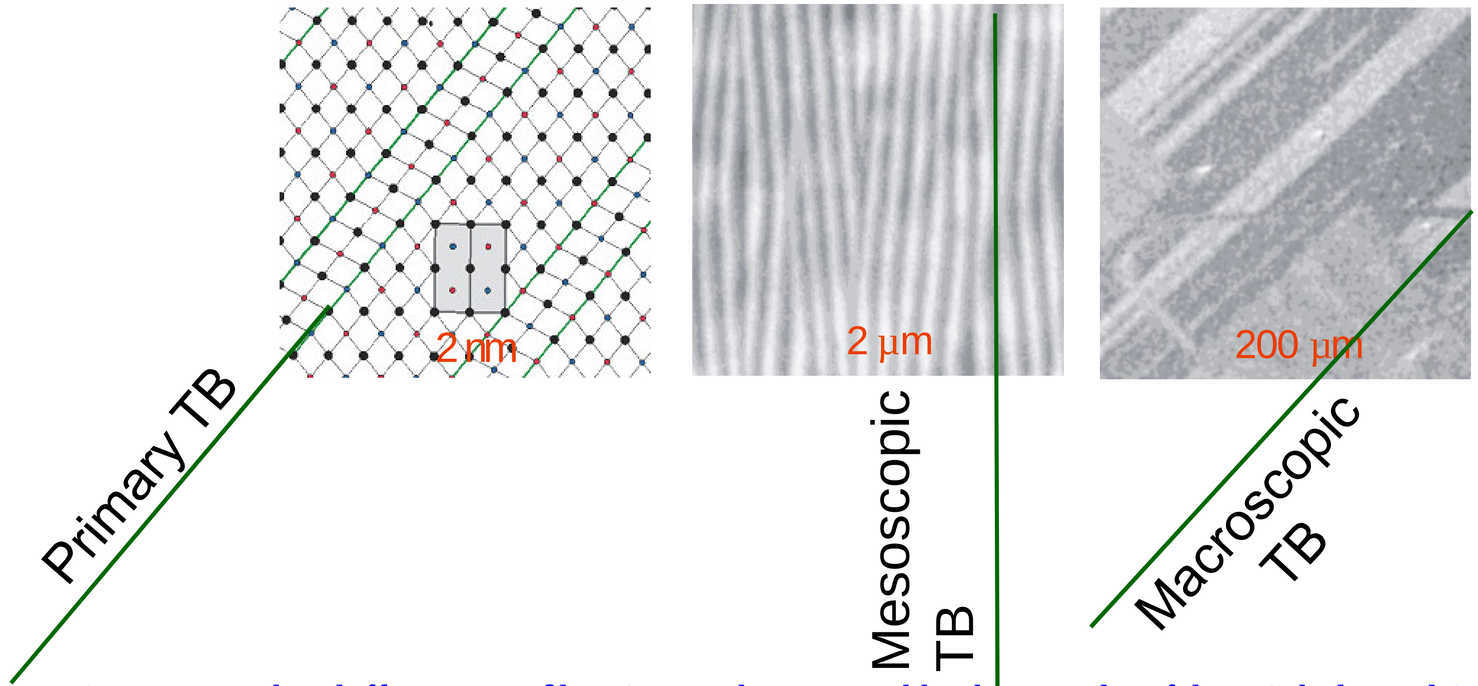


A hierarchical “twin within twins“ microstructure

A. L. Roytburd, Phase Transitions 45 (1993) 1



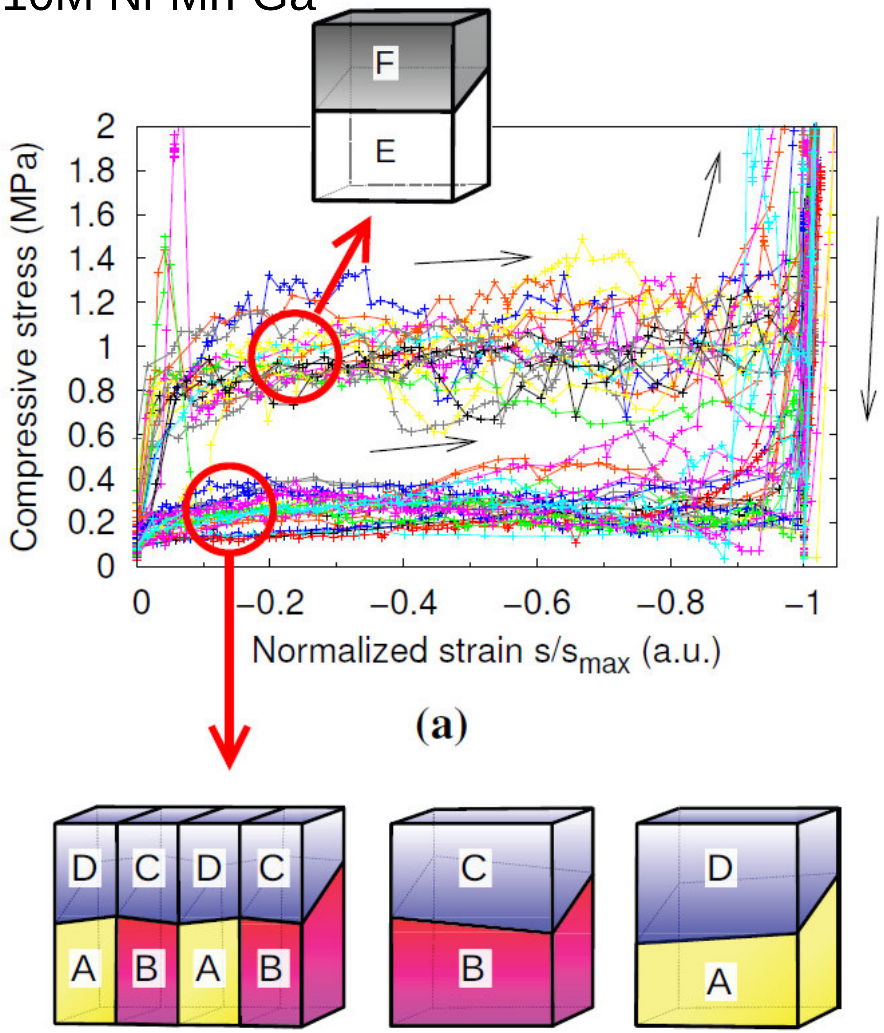
- Epitaxial Ni-Mn-Ga films



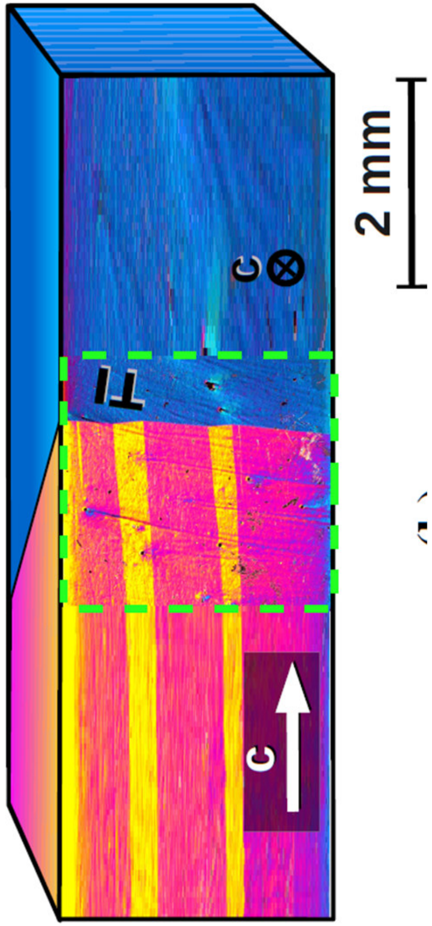
S. Kaufmann, R. Niemann, T. Thersleff, U. K. Rößler, O. Heczko, J. Buschbeck, B. Holzapfel, L. Schultz and S. Fähler, New J. of Physics 13 (2011) 053029

Mesoscopic twin boundaries

10M Ni-Mn-Ga



- ~1 MPa for type I TB



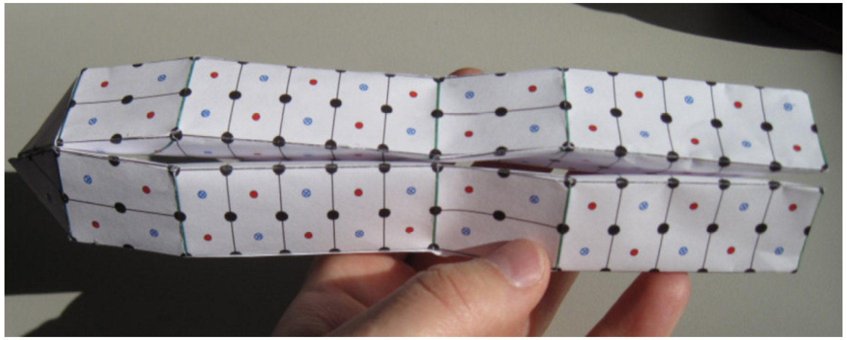
- ~0.2 MPa for type II TB

L. Straka, O. Heczko, H. Seiner, N. Lanska, J. Drahokoupil, A. Soroka, S. Fähler, H. Hänninen, A. Sozinov, Acta Mat. 59 (2011) 7450

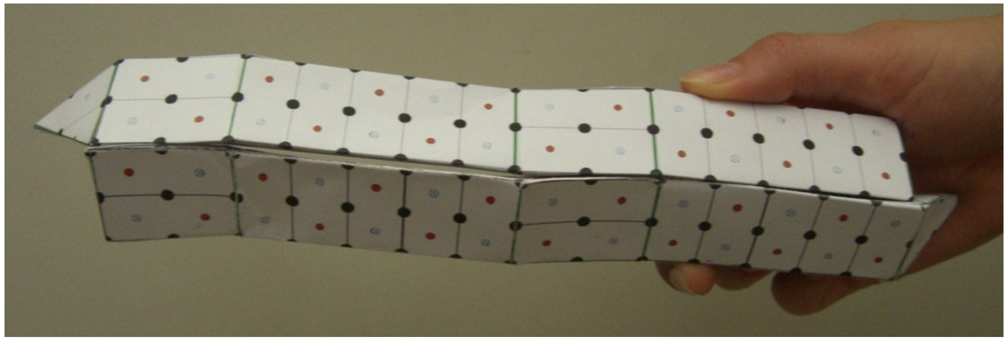
Monoclinic distortion of adaptive martensite

There are two ways to form mesoscopic twin boundaries:

Type I



Type II

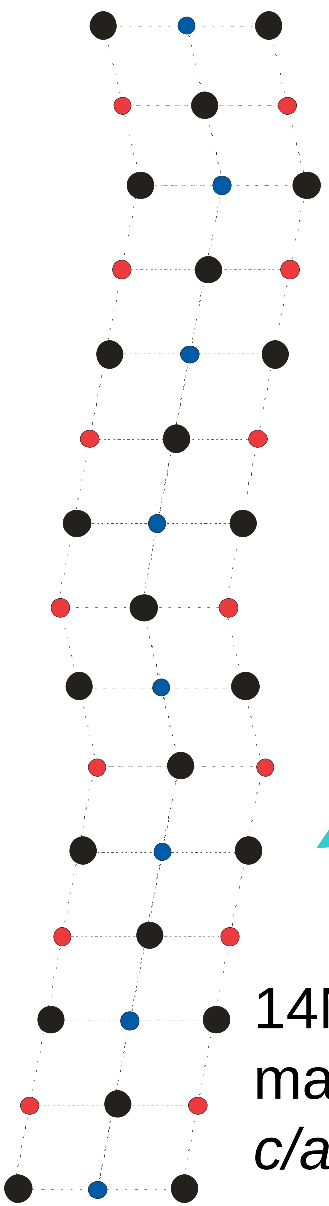


What is the origin of type I and II twin boundaries?

Martensitic Phases in Ni-Mn-Ga

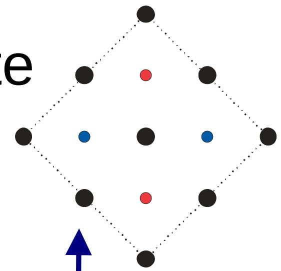
UNIVERSITÄT DUISBURG ESSEN

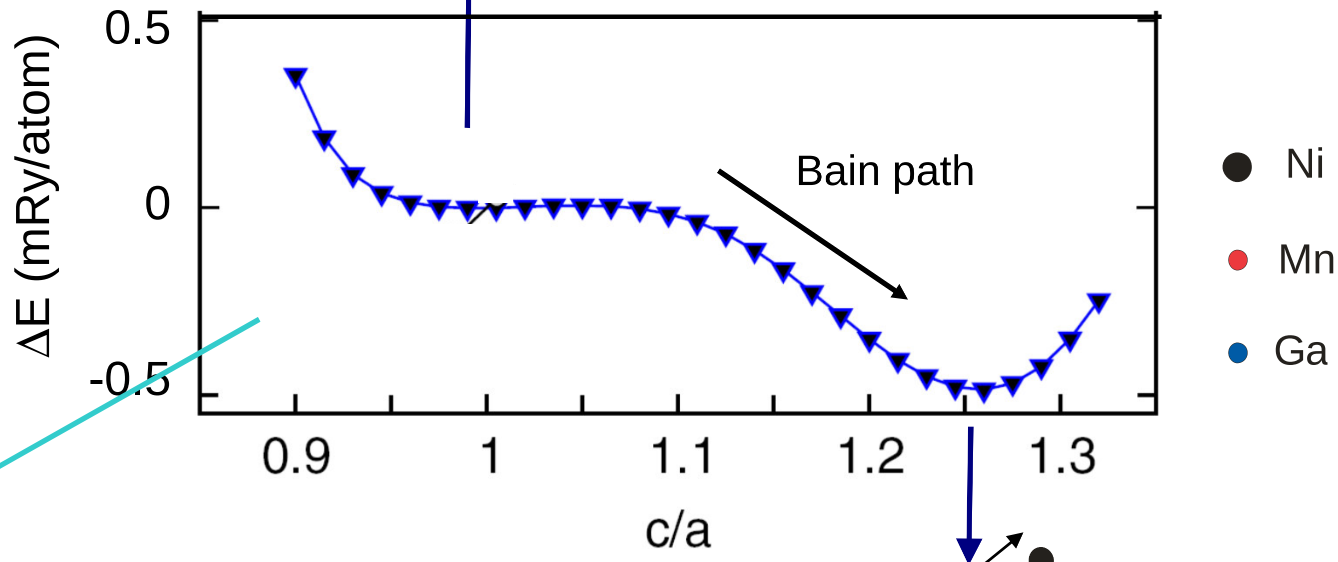
A3: P. Entel,
U. Duisburg-Essen



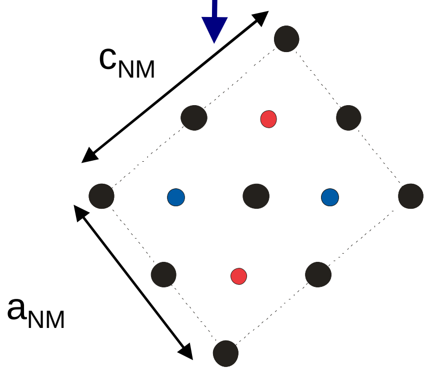
14M modulated martensite
$c/a_{14M} \cong 0.91$

Cubic austenite
$c/a = 1$



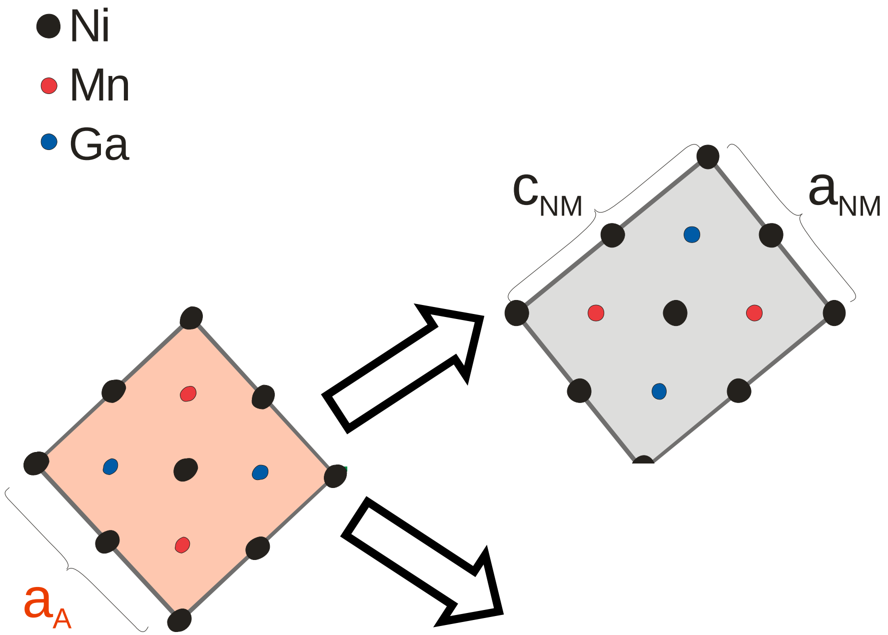


Tetragonal
NM martensite
$c/a \cong 1.25$



P. Entel et al., J. Phys. D **39**, 865-889 (2006)

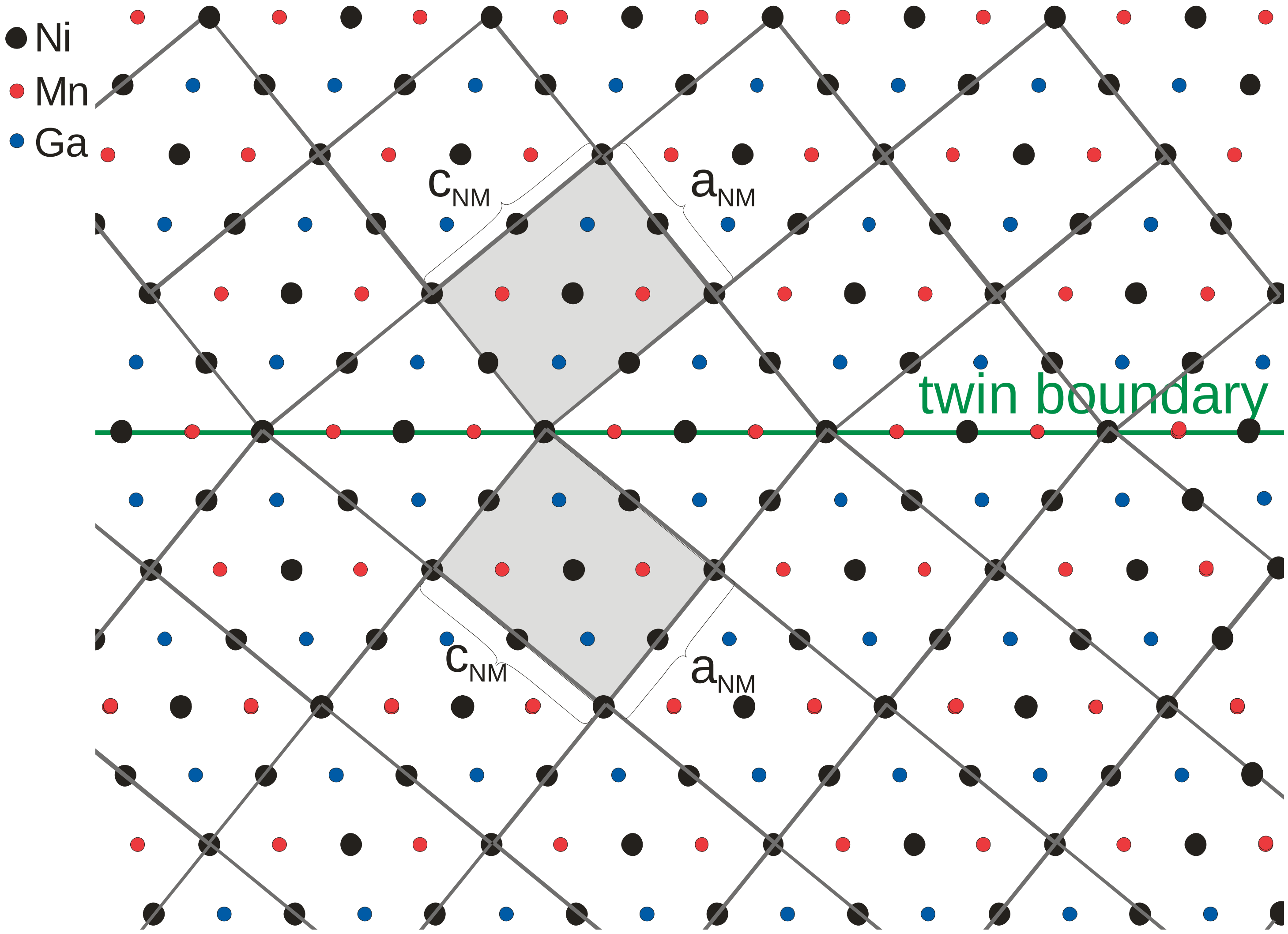
Martensitic transition



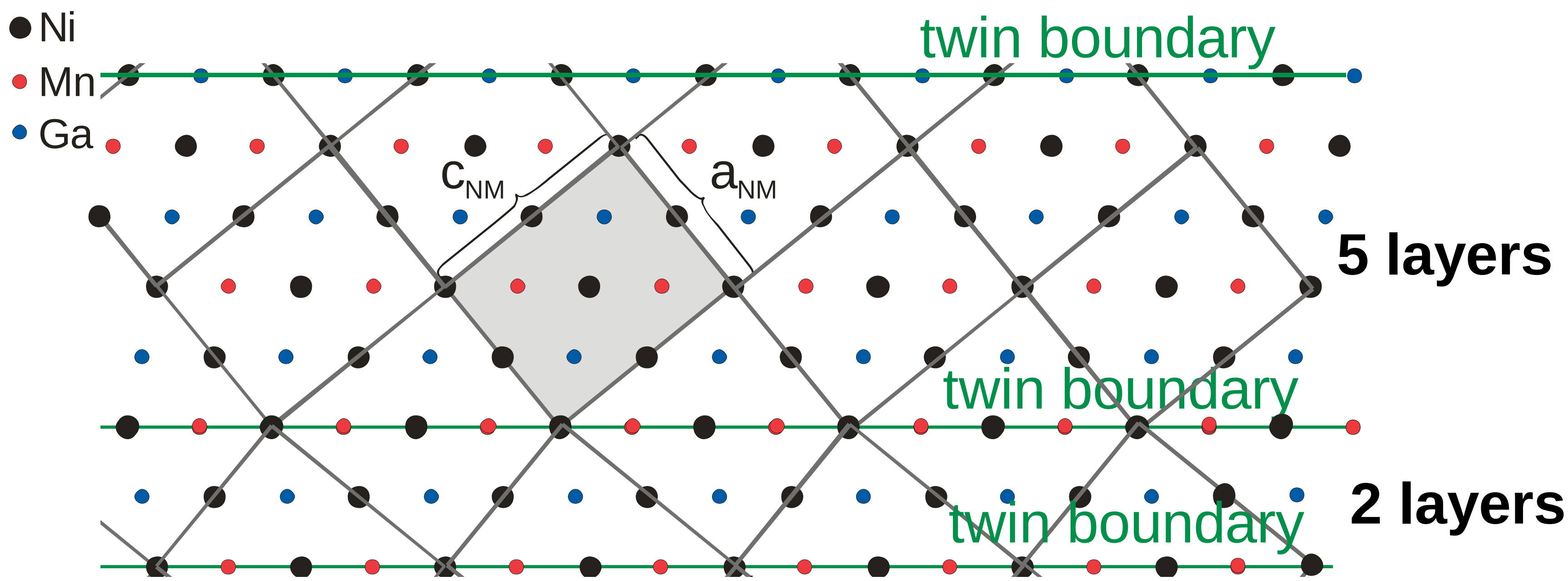
Austenite

Tetragonal Martensite (NM)

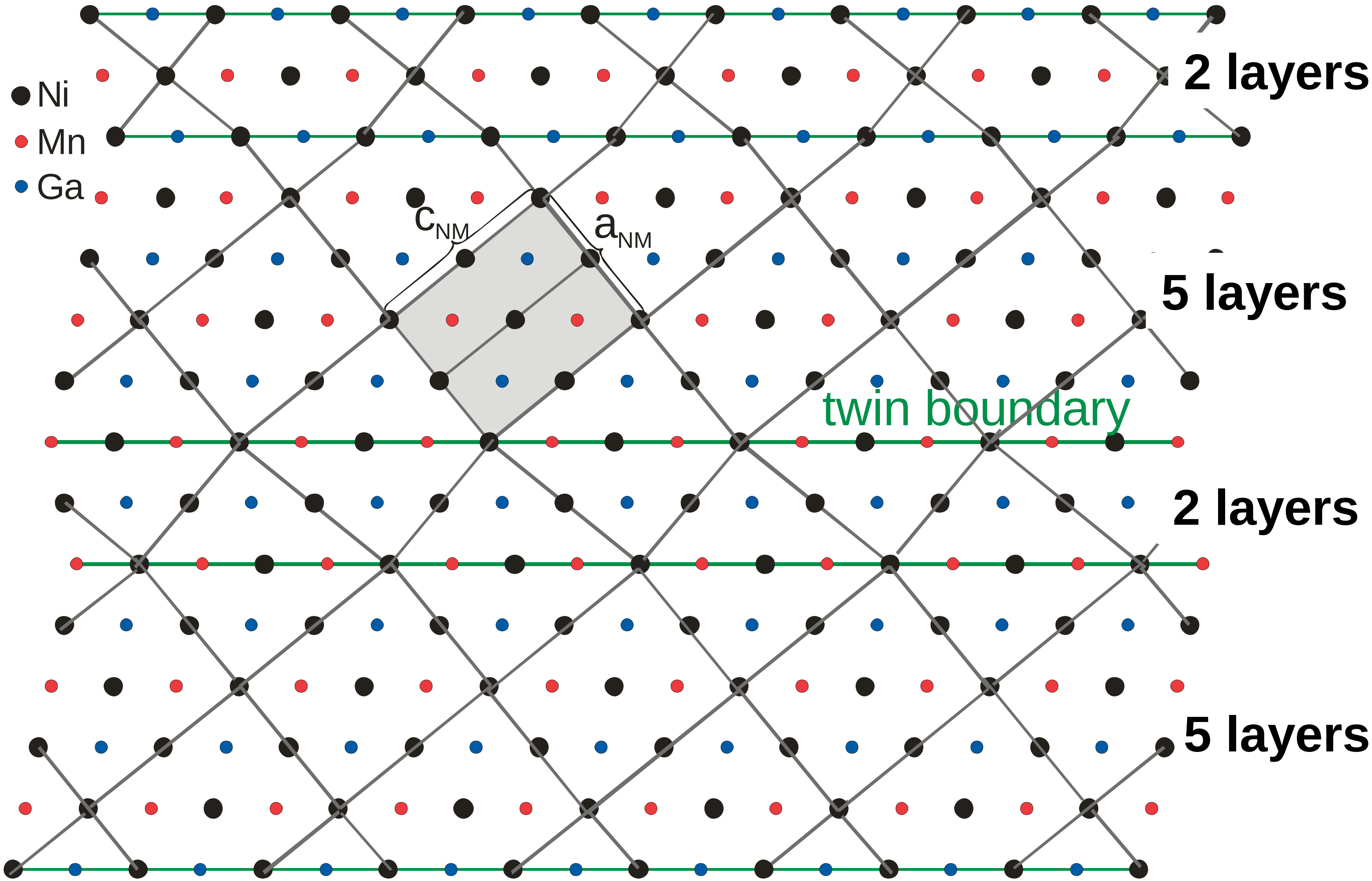
Twin boundaries in martensite



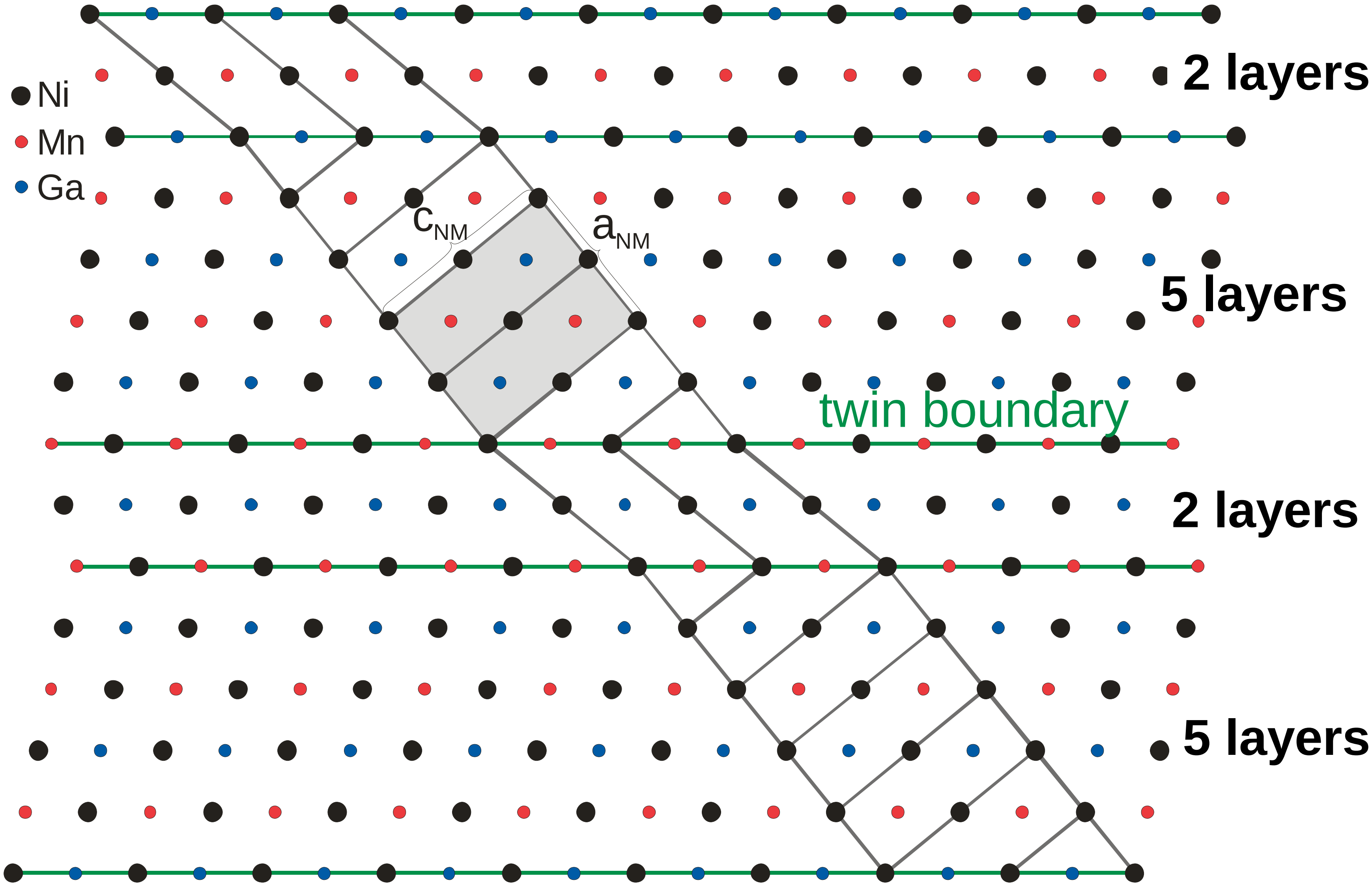
More twin boundaries



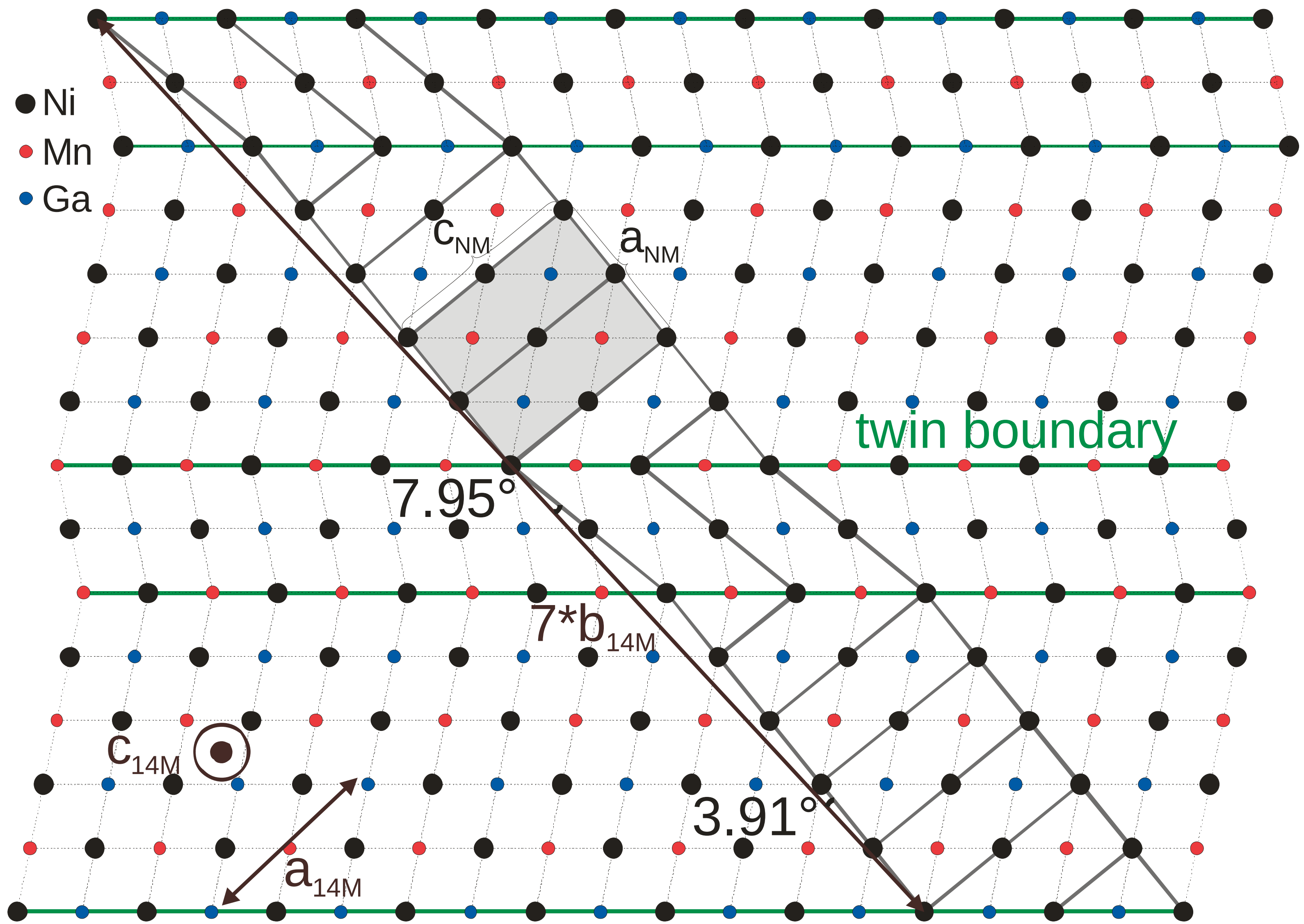
Nanotwinned martensite



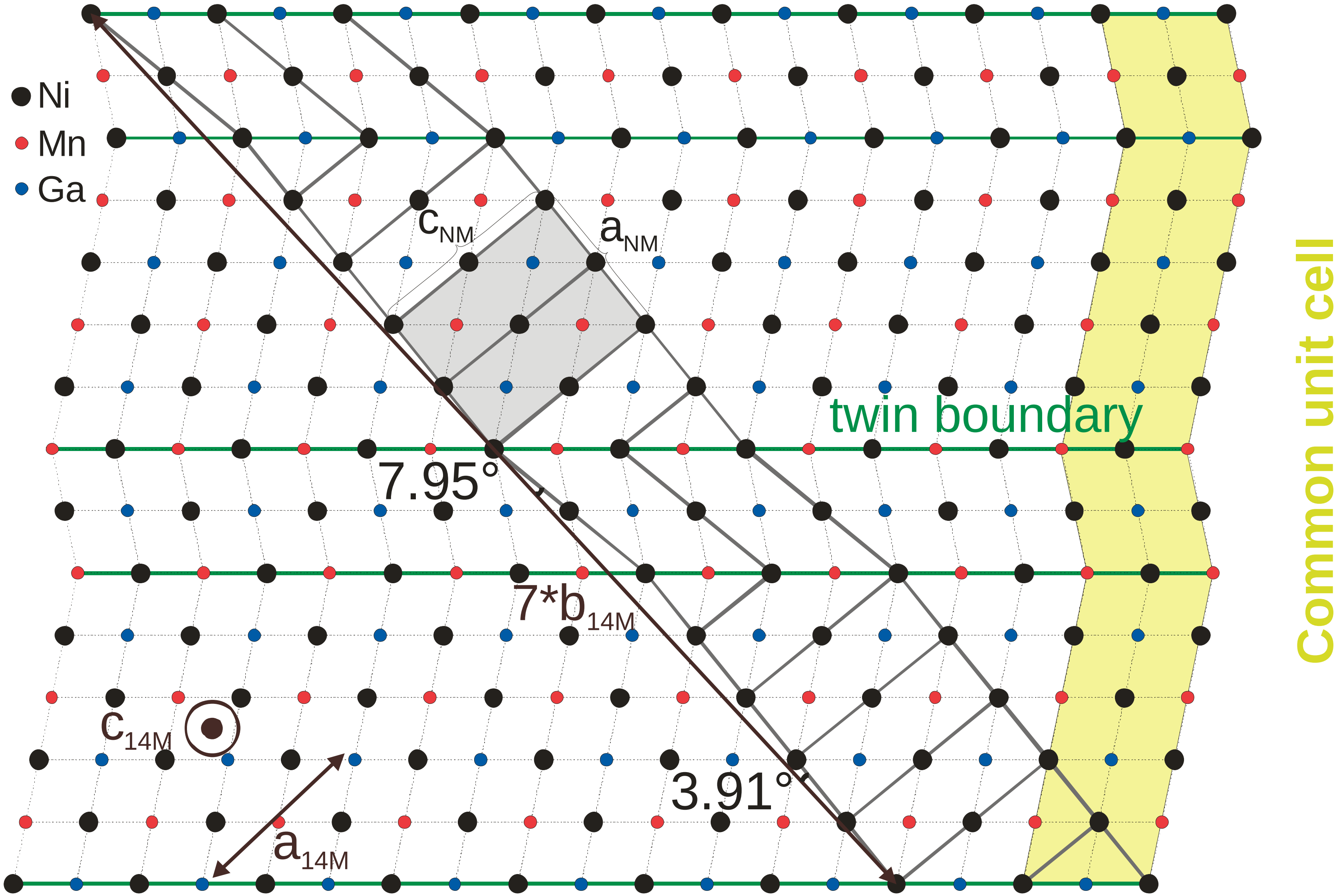
Nanotwinned martensite



Nanotwinned martensite

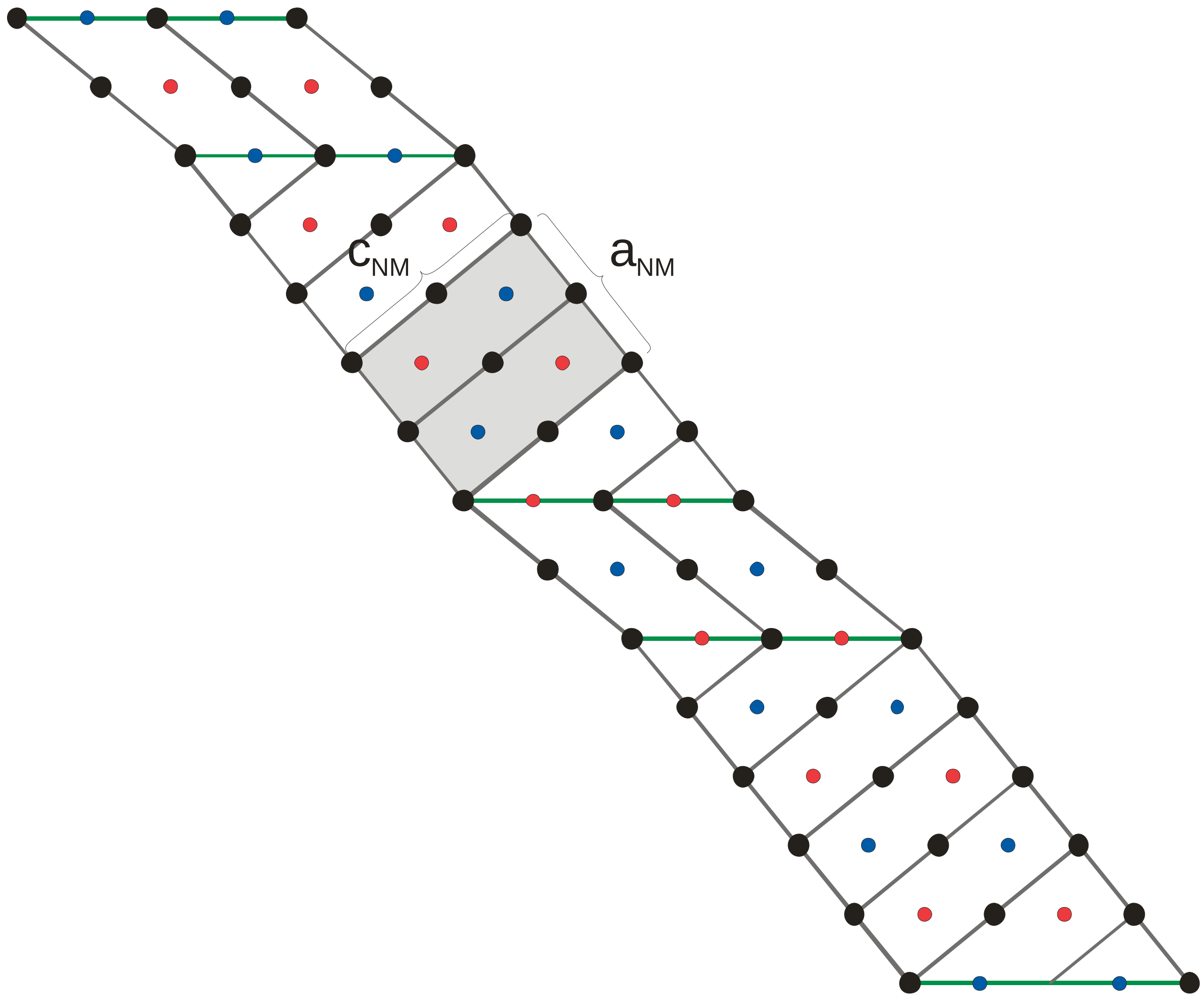


Modulated martensite

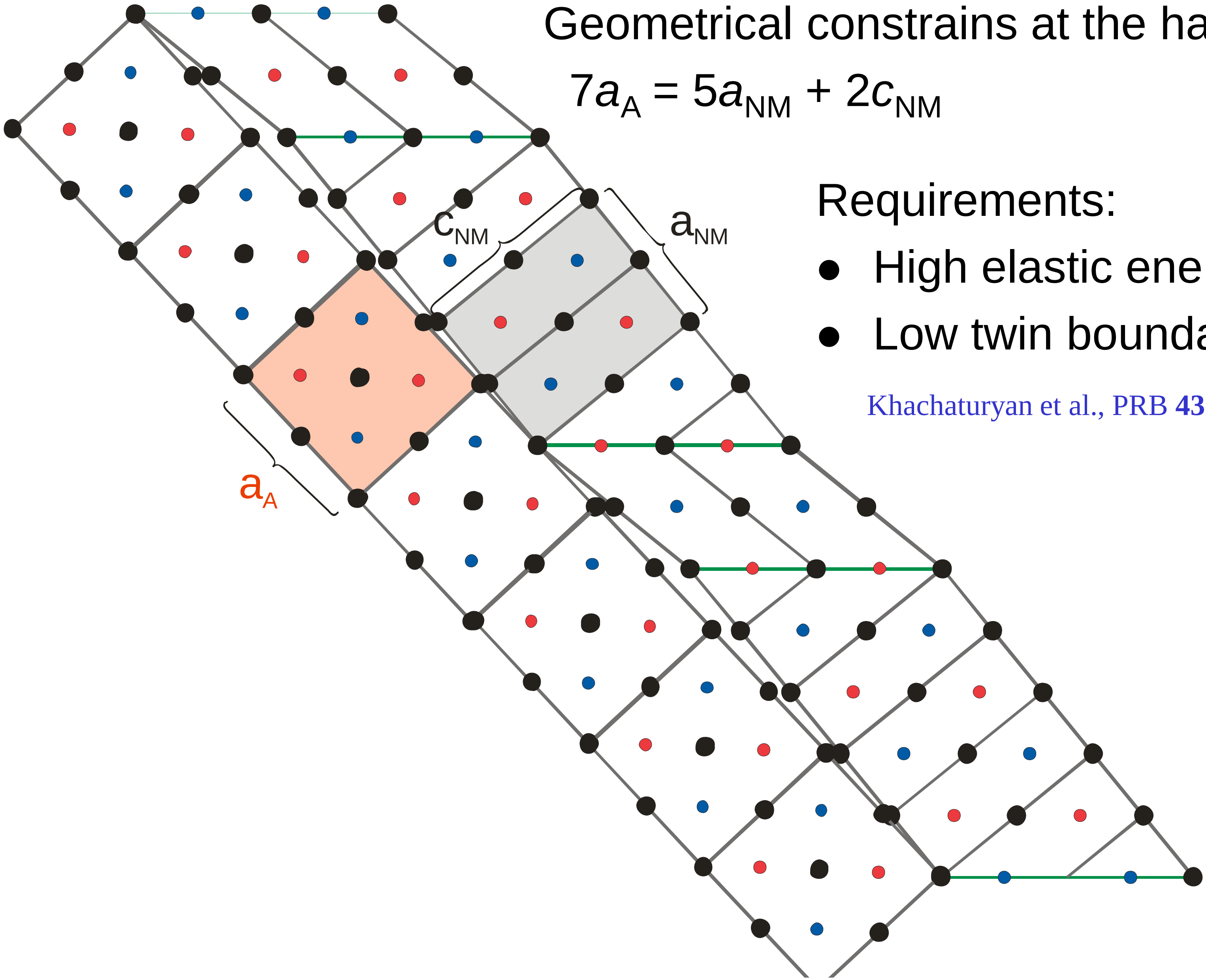


 S. Kaufmann, U.K. Rößler, O. Heczko, M. Wuttig, J. Buschbeck, L. Schultz, S. Fähler, Phys. Rev. Lett. 104 (2010) 145702

Modulated martensite



Adaptive martensite



Geometrical constrains at the habit plane

$$7a_A = 5a_{NM} + 2c_{NM}$$

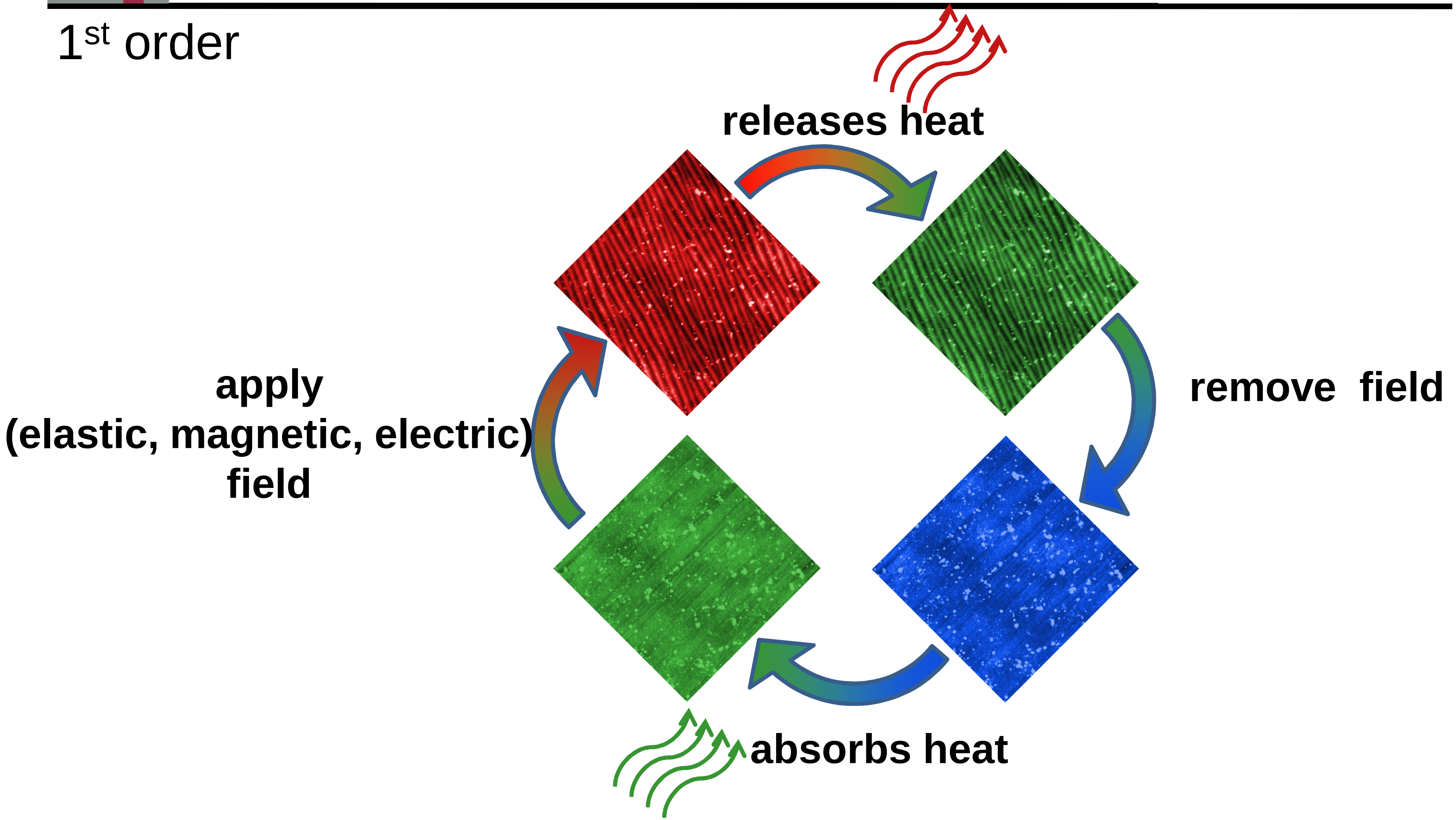
Requirements:

- High elastic energy
- Low twin boundary energy

Khachaturyan et al., PRB **43**, 13 (1991)

Multicaloric effects

1st order



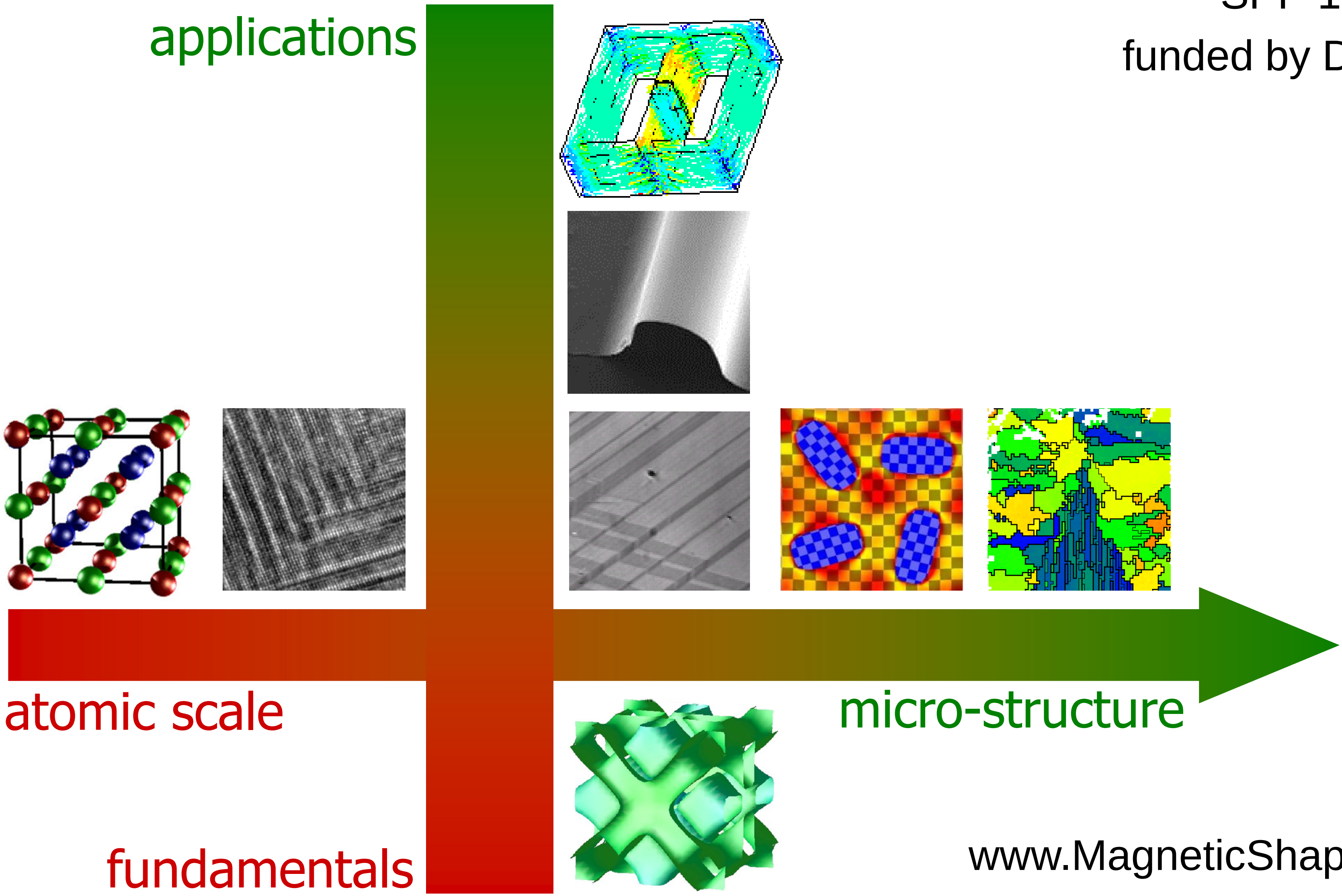
$$\Delta G = \Delta U - T\Delta S - p\Delta V + H\Delta M - \sigma\Delta\varepsilon + E\Delta P$$

Magnetic shape memory alloys

MSM

SPP 1239

funded by DFG



www.MagneticShape.de

Further reading

- B. D. Cullity, C. D. Graham, *Introduction to Magnetic Materials*, 2nd Ed. Wiley, (2009), Chapter 8: *Magnetostriction and the effects of stress*
- É. Du Trémolet de Lacheisserie, D. Gignoux, M. Schlenker, *Magnetism – Fundamentals*, Kluwer (2003), Chapter 12: *Magnetoelastic effects*
- Special Issue: *Magnetic Shape Memory Alloys*, Adv. Eng. Mat. 14(8) (2012)
- A brief introduction on magnetic shape memory alloys with animated gifs: http://www.MagneticShape.de/funktionsprinzip.html
- O. Heczko, N. Scheerbaum, and O. Gutfleisch, *Magnetic Shape Memory Phenomena* (Ch. 14), in J. P. Liu, E. Fullerton, O. Gutfleisch, and D.J. Sellmyer (eds), *Nanoscale Magnetic Materials and Applications*, Springer Science, 399 (2009).