Summer School of Advanced Functional Materials
Shenyang, China, July 9-10, 2008

Ferromagnetic Semiconductors
- Physics and Material Science -

H. Ohno

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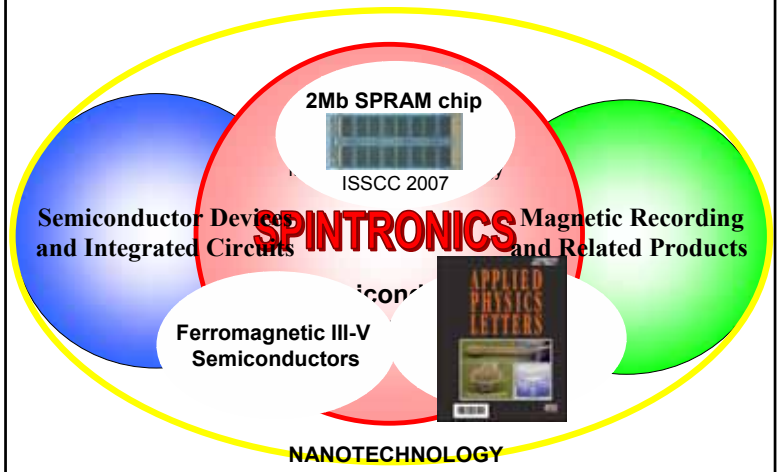
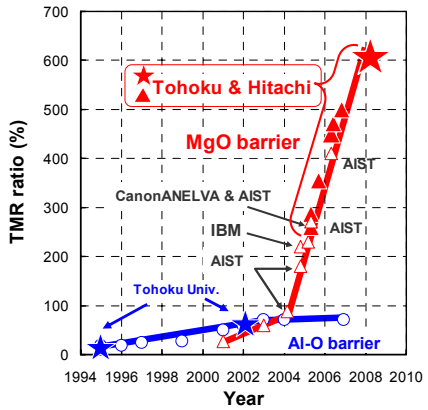
Work partly supported by the "Research and Development for Next-Generation Information Technology" program from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

Why spintronics is important



TMR ratio of MgO-MTJs

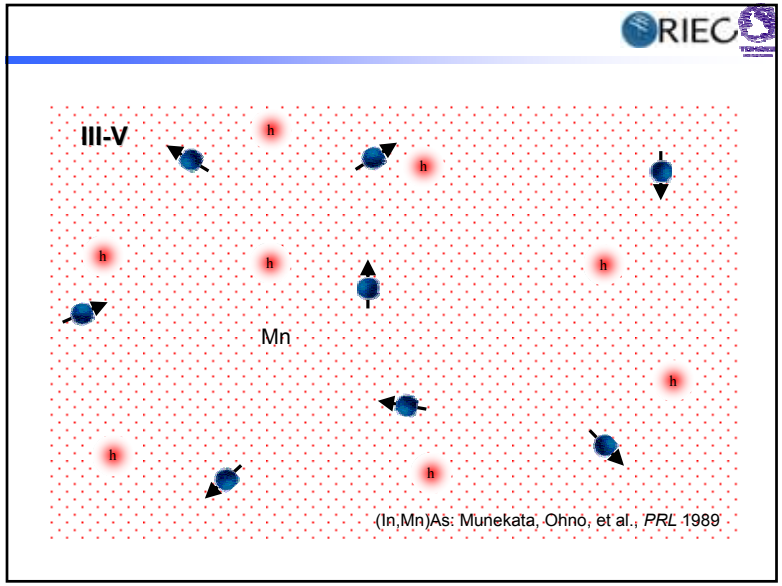


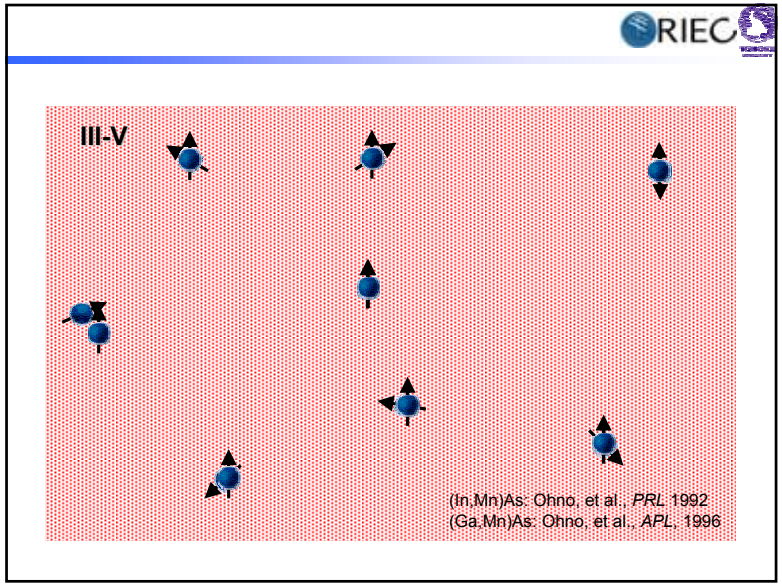
604%@300K
(1144% @5K)

Intermag 2008 HR-01
S. Ikeda et al.

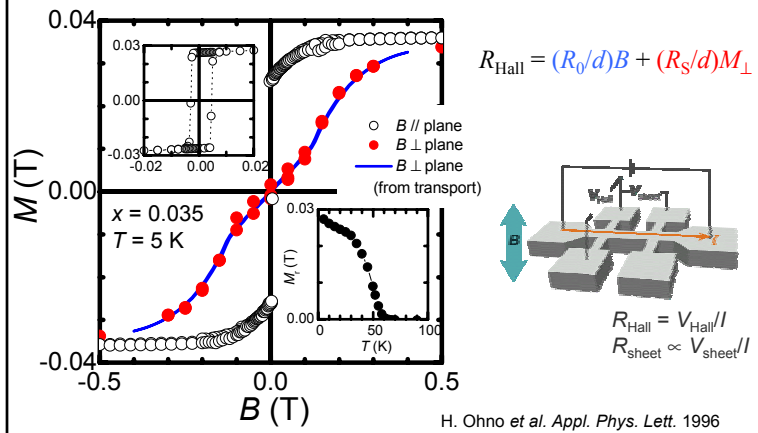
For MgO barrier MTJs,
AIST(S.Yuasa et al.): JJAP43(2004)L588, Nature Mater. 3(2005)868; APL89(2006)042505.
IBM (S.S.P.Parkin et al.): Nature Mater. 3(2005)862.
CanonANELVA & AIST: APL 86(2005) 092502
Tohoku Univ. & Hitachi:
JJAP44(2005)L587;JJAP44(2005)L1442; JAP99(2006)08A907; APL 89(2006)042506. APL89(2006)232510; APL90(2007)212507. IEEE T-ED 54(2007)991.

1. Ferromagnetic III-V semiconductors
2. Current-induced domain wall motion
3. Toward high T_C





Magnetic Properties of (Ga,Mn)As



$R_{Hall} = (R_0/d)B + (R_S/d)M_\perp$

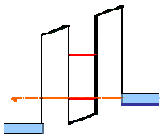
$R_{Hall} = V_{Hall}/I$

$R_{sheet} \propto V_{sheet}/I$

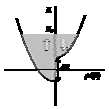
H. Ohno *et al. Appl. Phys. Lett.* 1996
H. Ohno *Science* 1998

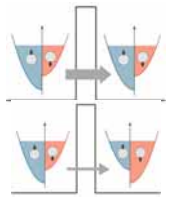
Ferromagnetism and Semiconductor Devices

spontaneous spin-splitting of bands

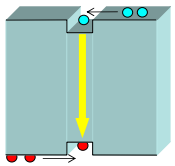


Resonant Tunneling Diodes
Appl. Phys. Lett. **73**, 363 (1998)

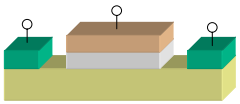




Magnetic Tunnel Junctions



Light Emitting Diodes – spin LED –
Nature **402**, 790 (1999)



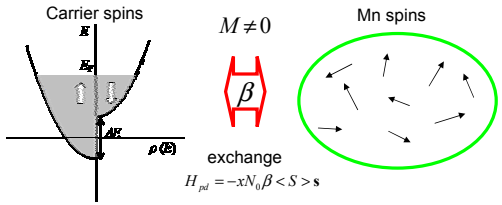
Field Effect Transistors
Nature **408**, 944 (2000)

p-d Zener model of ferromagnetism

Ferromagnetic (Ga,Mn)As

Mn acts as a source of spin and hole

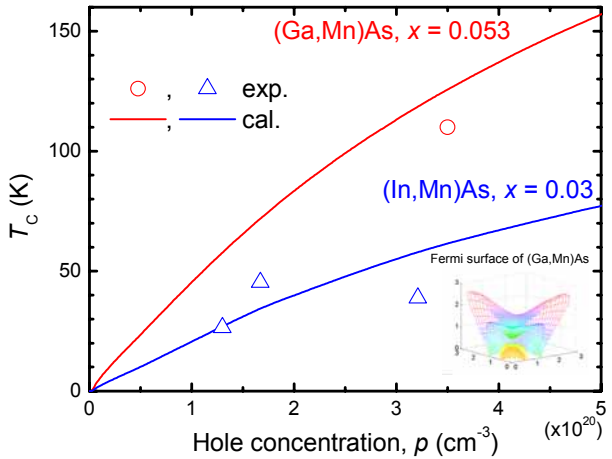
H. Ohno *et al. Appl. Phys. Lett.* 1996
H. Ohno *Science* 1998



$$T_c = \frac{xN_0S(S+1)A_F\rho(E_F)\beta^2}{12k_B}$$

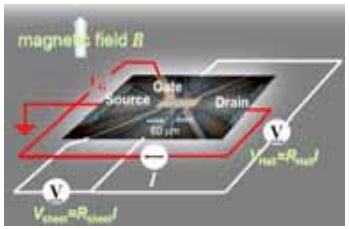
T. Dietl, *et al. Science* **287**, 1019 (2000) and *PRB* **63**, 195205 (2001)
also Koenig *et al. Phys. Rev. Lett.* 2000

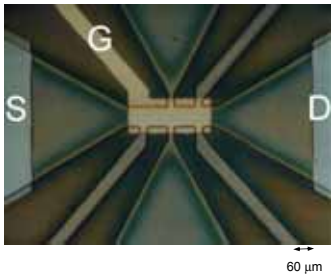
Comparison of exp. and calculated T_C



Electric-Field Control of Ferromagnetism

95/5 nm	Au/Cr
800 nm	polyimide
5 nm	$(In_{0.97}Mn_{0.03})As$
10 nm	InAs
400 nm	$(Al_{0.6}Ga_{0.4})Sb$
100 nm	AlSb
	GaAs sub.



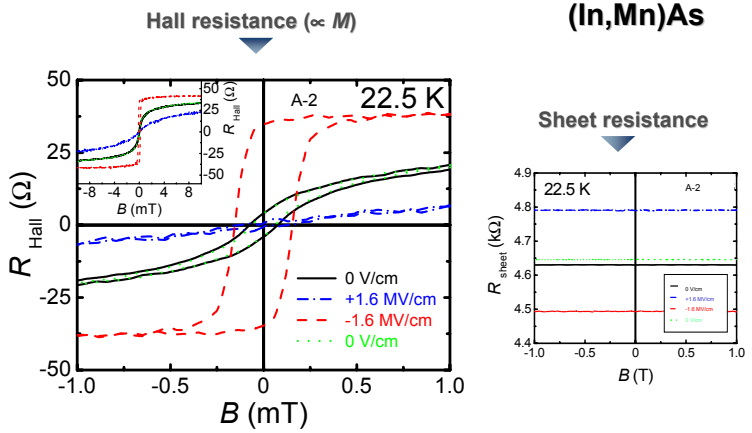


$R_{Hall} = (R_0/d)B + (R_S/d)M$

(ordinary Hall effect + **anomalous Hall effect**)

Ohno *et al., Nature* 2000

Magnetization Curves under Gate Bias

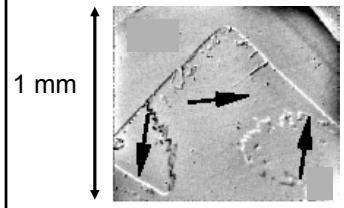


Ohno *et al., Nature* 2000

Magnetism in Everyday Life

1. Ferromagnetic III-V semiconductors
2. Current-induced domain wall motion
3. Toward high T_C

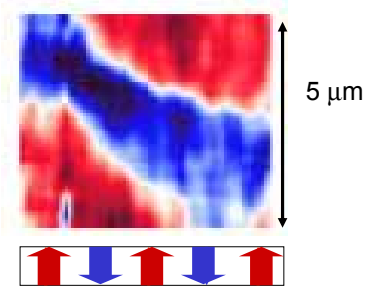
Well defined domains in (Ga,Mn)As



Welp *et al.*, *PRL* 2003

See Sugawara et al. *PRL* 2008 for Lorenz microscope observation

compressive strain
in-plane easy axis
90° domains



Shono *et al.*, *APL* 2002

tensile strain
perpendicular easy axis
stripe domains

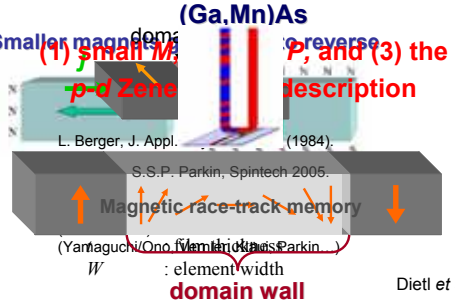
Why domain wall and why in (Ga,Mn)As?

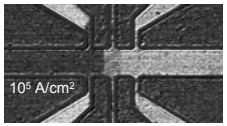
Physics:

Addresses physics of nontrivial interaction between carrier-spins and localized spin texture and its consequences

Technology:

Electrical manipulation of magnetization





Yamanouchi *et al.* ***Nature*** 2004

$$\delta = \pi\sqrt{\frac{A_s}{K_u}} \approx 17\ \text{nm}$$

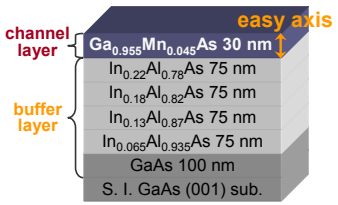
$A_s \sim 9 \times 10^{-14}$ J/m

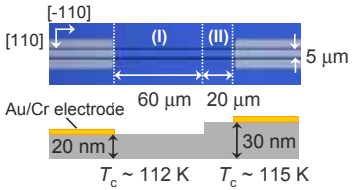
$K_u \sim 3 \times 10^{3}$ J/m^3

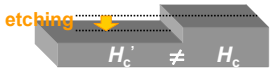
Dietl *et al. Phys. Rev. B* **64**, 241201(R) (2001)

Domain wall velocity

Sample structure







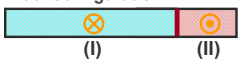
Patterning of coercive force H_c by etching of (Ga,Mn)As

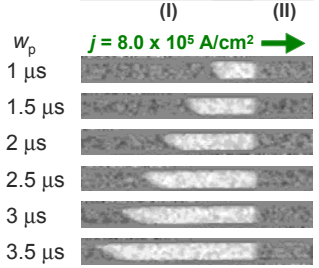
Preparation of domain wall

Domain wall velocity

T_n = 100 K

Initial configuration



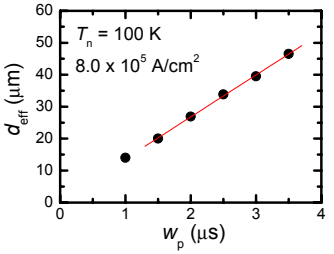


MOKE: Magneto-optical Kerr effect image

- DW moves in the opposite direction of current pulse
- d_{eff} depends linearly on pulse width

Effective DW displacement

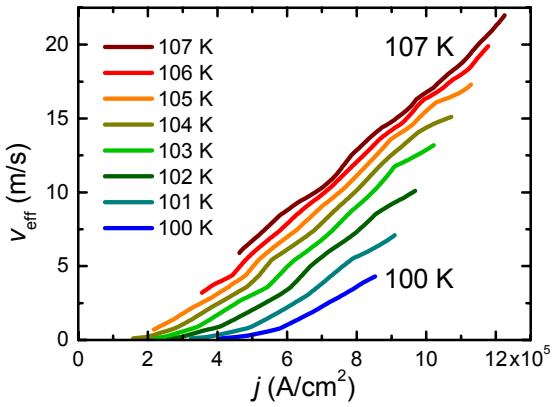
d_{eff} : the area swept by DW divided by channel width



Effective DW velocity

v_{eff} : linear slope of d_{eff} - w_p for d_{eff} > 15 μm

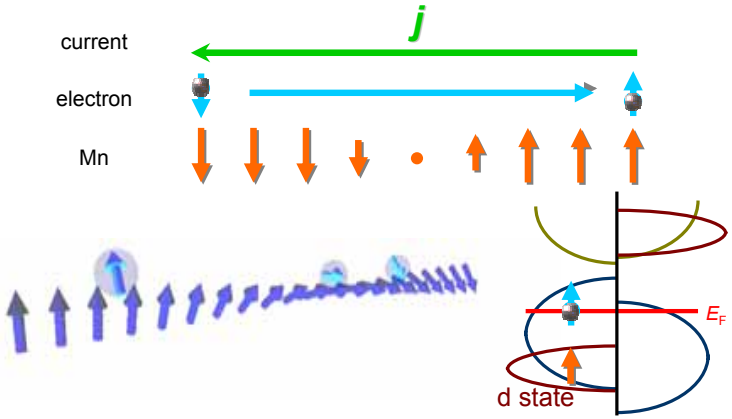
Domain wall velocity



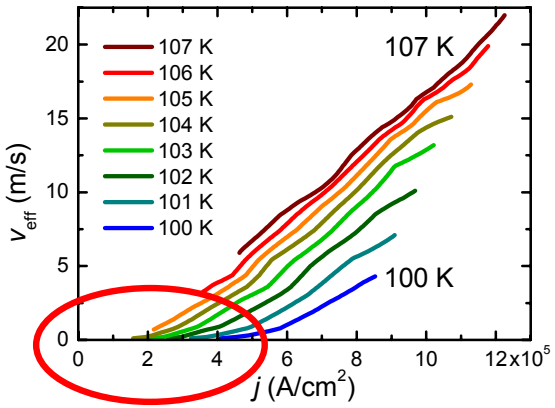
M. Yamanouchi *et al.*, *Phys. Rev. Lett.* **96**, 096601 (2006)

Mechanism

- **Adiabatic spin transfer (conservation of angular momentum)**

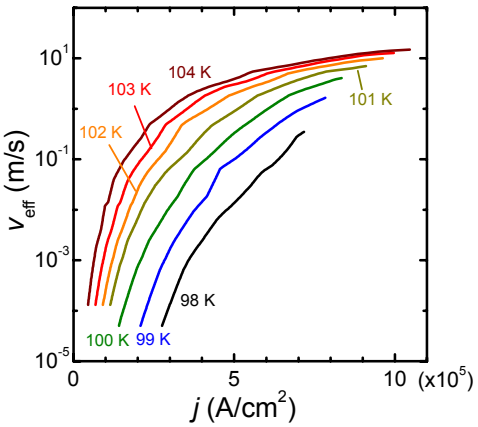


Domain wall velocity



M. Yamanouchi *et al.*, *Phys. Rev. Lett.* **96**, 096601 (2006)

Velocity: Sub-threshold regime



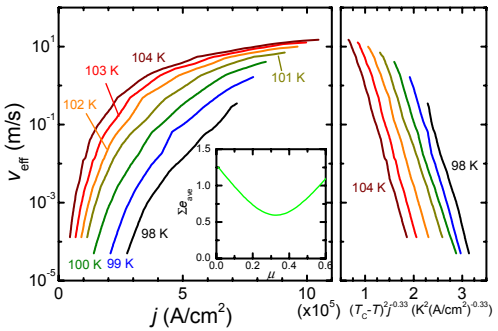
Current assisted domain wall creep

$$\ln(v(H)) = v_0' - \frac{U_{cw}}{k_B T}\left(\frac{H_{crit}}{H}\right)^{\mu}$$

Lemerle *et al. PRL* **80**, 894 (1998)

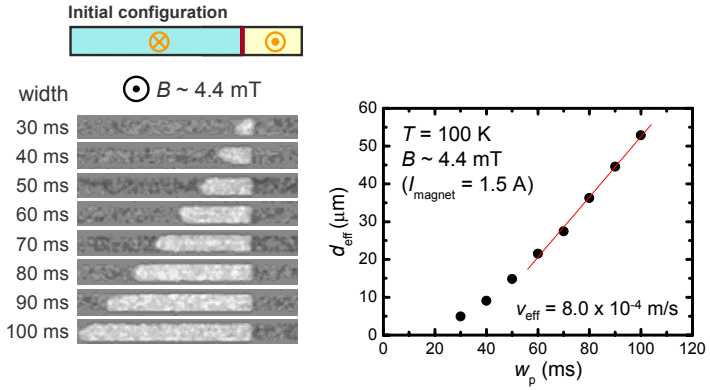
$$\ln(v_{eff}) = a - bj^{-\mu}$$

μ = 0.33



DW motion by magnetic field

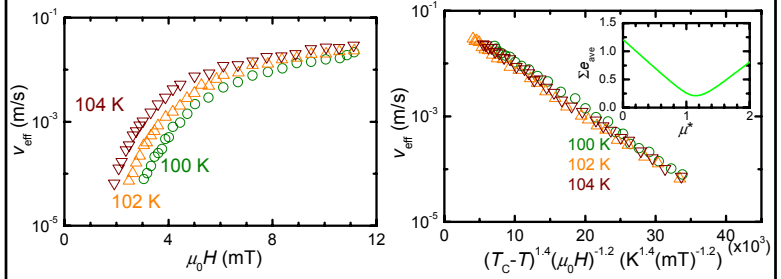
100 K



DW velocity (field-drive)

$$\ln(v_{eff}) = a - bH^{-\mu}$$

μ = 1.2



Critical exponents

$$\ln(v_{eff}) = a - bj^{(-\mu)} \left(\text{or } H^{(-\mu)}\right)$$

	current drive	field drive
μ	0.33±0.06	1.2±0.1
universality class	not previously known	random-field*

* P. Chauve, T. Giamarchi, and P. Le Doussal, Phys. Rev. B **62**, 6241 (2000)

Yamanouchi, Ieda, Matsukura, Barnes, Maekawa and Ohno, *Science*, **317**, 1726 (2007)

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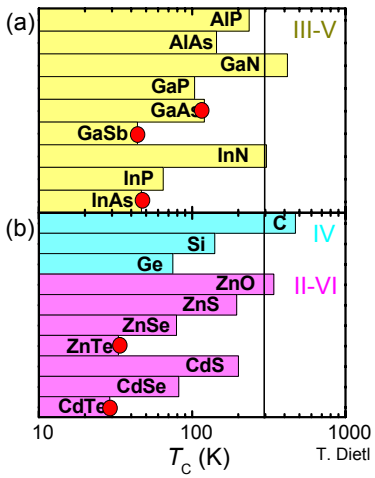
T_C by the *p-d* Zener Model

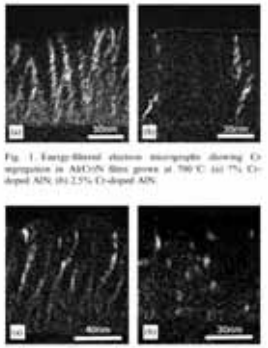


x_{Mn} = 0.05
p = 3.5 x 10^{20} cm^{-3}

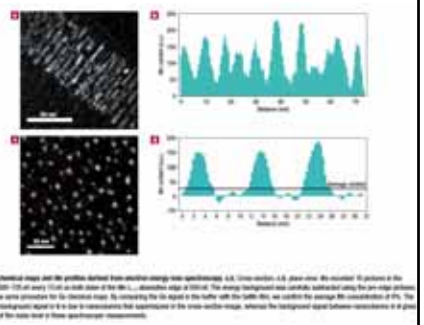
$$T_c \propto xN_0\rho(E_F)\beta^2$$

T. Dietl *et al. Science* 2000, *Phys. Rev. B* 2001

(Al,Cr)N and Ge:Mn



L. Gu *et al.*, *JMMM*, **290-291**, 1395 (2005)

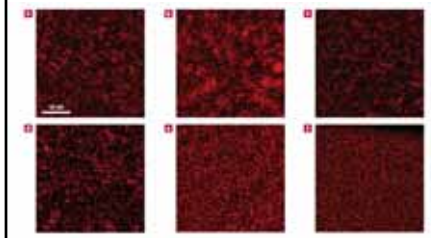


M. Jamet *et al.*, *Nature Mat.*, **5**, 653 (2006)

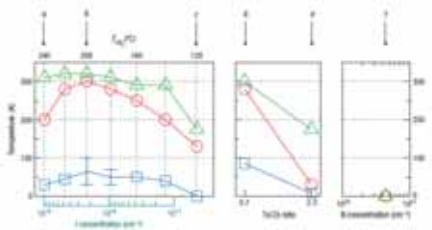
Four different cases

- **Metallic random alloy**
- **Electronic phase separation**
- **Chemical phase separation on the same lattice**
  - **can stabilize a structure that does not exist in its bulk form**
  - **a new route to nanostructure formation**
- **Precipitates with different crystal structures**

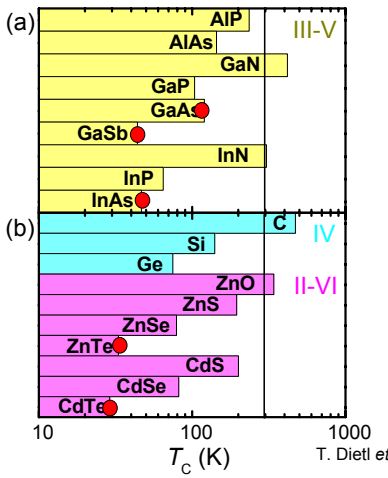
The case of $Zn_{0.94}Cr_{0.06}Te$



S. Kuroda *et al. Nature Materials* 2007
(Univ. Tsukuba)



T_C by the *p-d* Zener Model



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$$T_c \propto x\rho(E_F)\beta^2$$

T. Dietl *et al. Science* 2000, *Phys. Rev. B* 2001

Why spintronics is important