# Recent developments in spintronic


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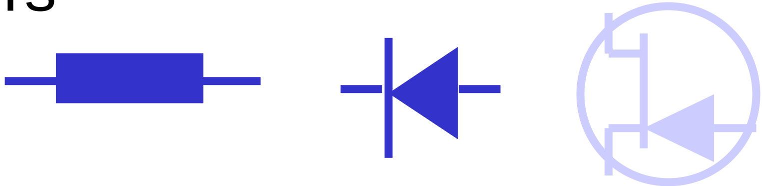
**in collaboration with**

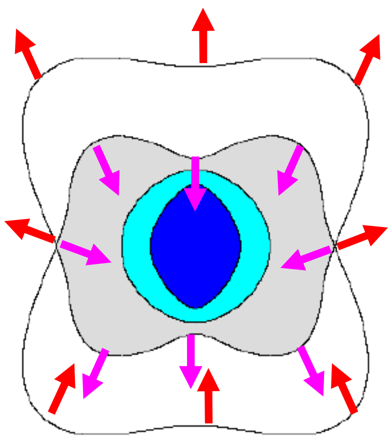

***Hitachi Cambridge, University of Texas, Texas A&M University***

- **Spintronics in footsteps of classical electronics**

  from resistors and diodes to transistors

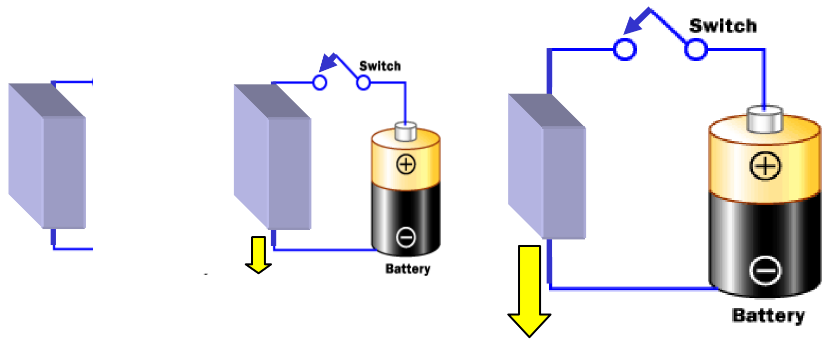


- **Spintronics - ferromagnetism & spin-orbit coupling**

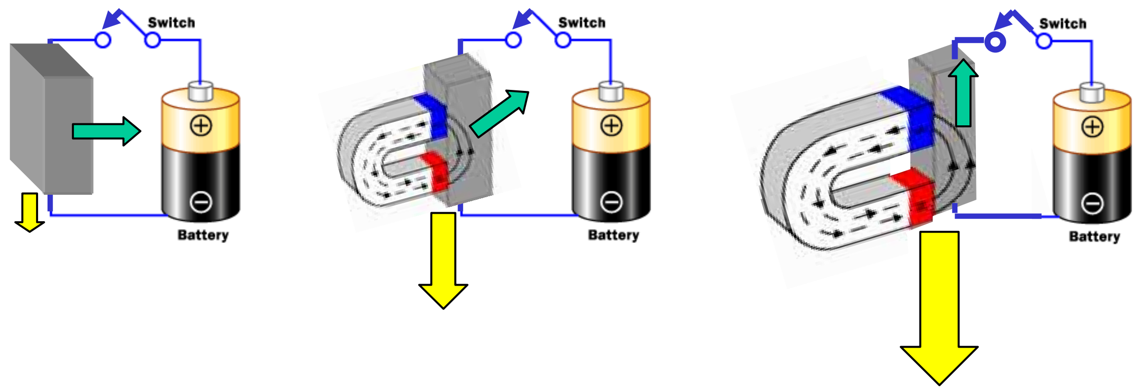


# Resistor

classical

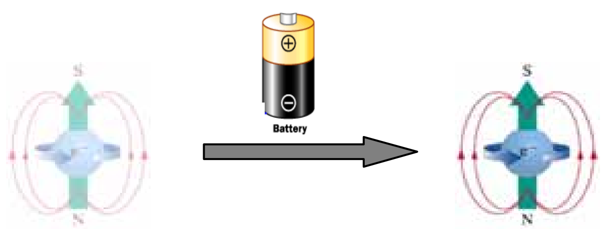


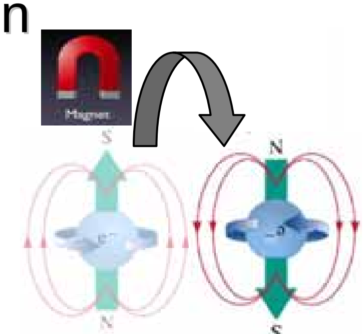

spintronic

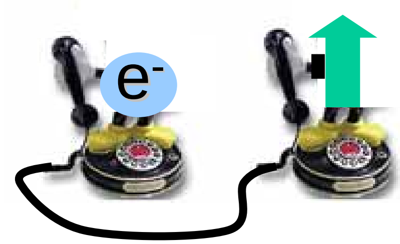



external manipulation of
charge & spin

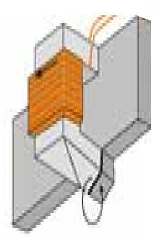
internal communication between
charge & spin






*replaced*

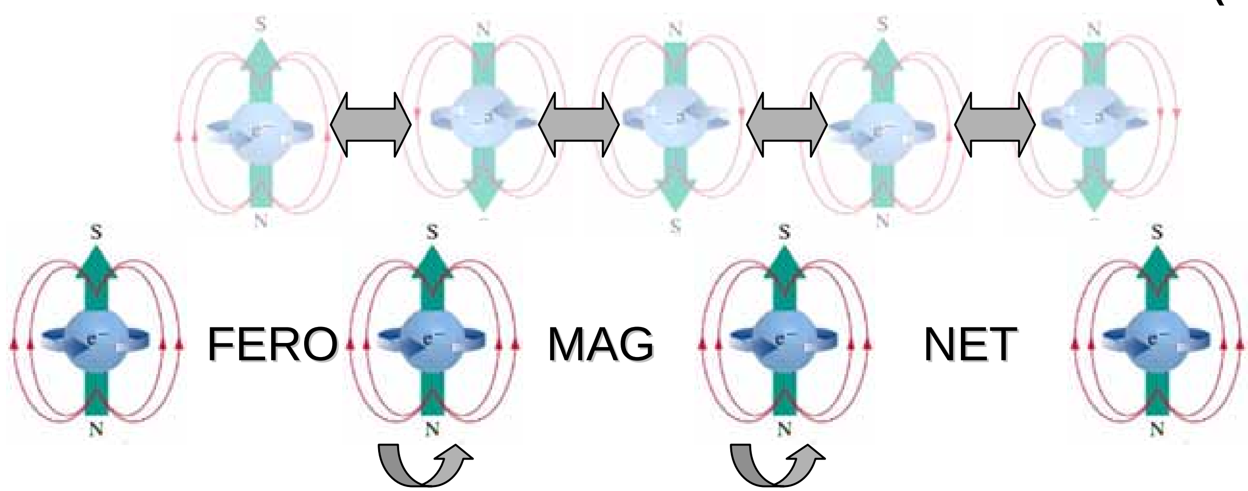


*sensors in magnetic storage*

Non-relativistic many-body 

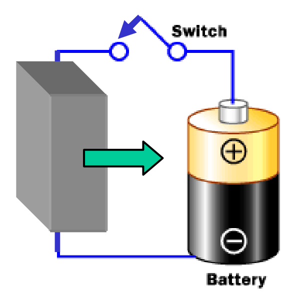

Pauli exclusion principle & Coulomb repulsion → **Ferromagnetism**

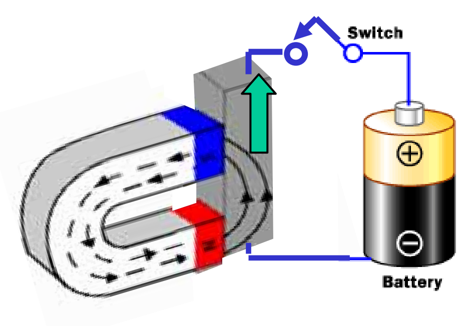
*total wf antisymmetric* = *orbital wf antisymmetric* * *spin wf symmetric (aligned)*

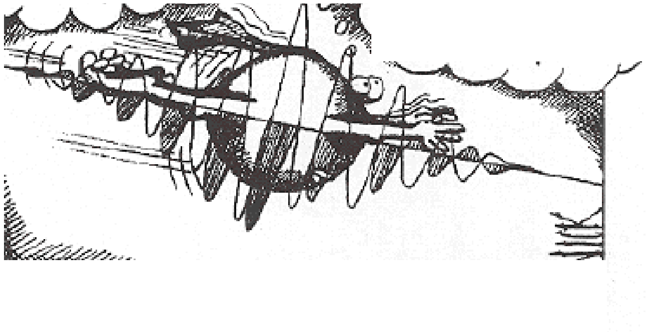



- **Robust** (can be as strong as bonding in solids)

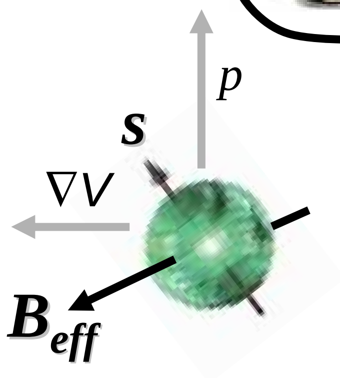
- **Strong coupling to magnetic field**
  (weak fields = anisotropy fields needed only to reorient macroscopic moment)






Relativistic "single-particle"

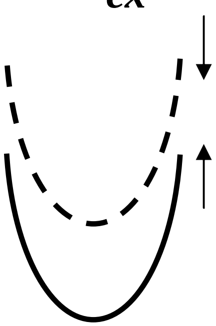

$$H_{SO} = \vec{s} \cdot \vec{B}_{eff}$$

$$\vec{B}_{eff} = \frac{1}{2m^2c^2} (\nabla V) \times \vec{p}$$

**Spin-orbit coupling**

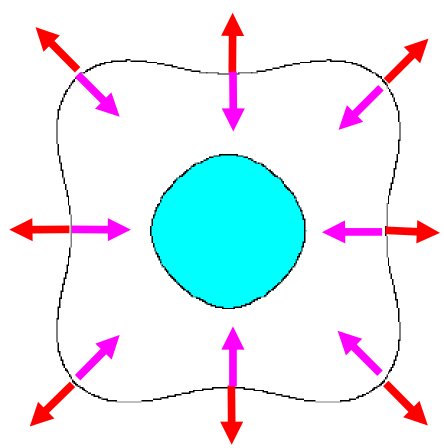
(Dirac eq. in external field $\nabla V(\mathbf{r})$ & 2nd-order in $v/c$ around non-relativistic limit)

$\boldsymbol{B_{ex}}$



FM without SO-coupling

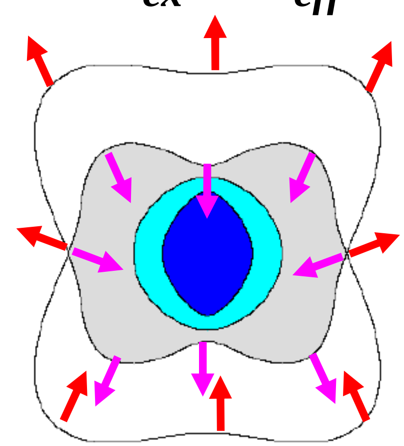
$\boldsymbol{B_{eff}}$



GaAs valence band

As *p*-orbitals → large SO

$\boldsymbol{B_{ex} + B_{eff}}$



GaMnAs valence band

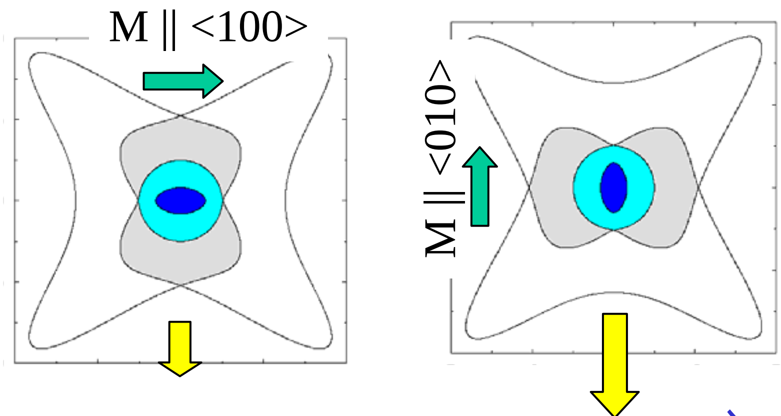
tunable FM & large SO

# AMR

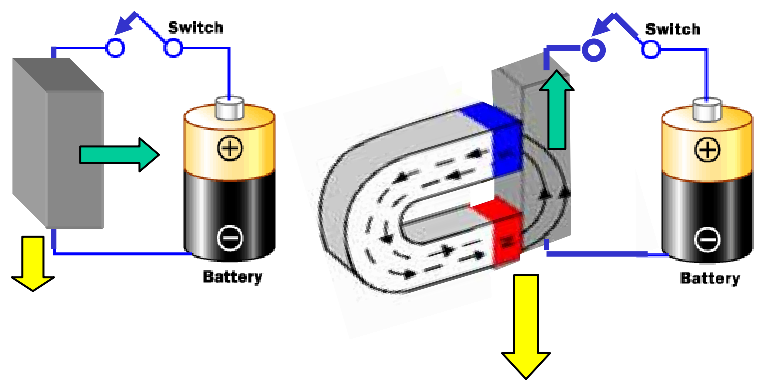
## Ferromagnetism: sensitivity to magnetic field

## SO-coupling: anisotropies in Ohmic transport characteristics

GaMnAs

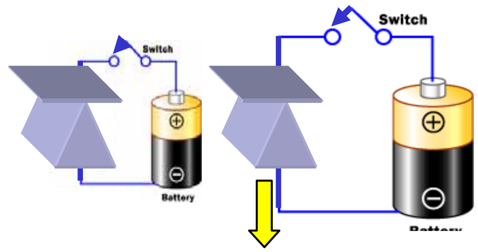



**Band structure depends on** $\vec{M}$

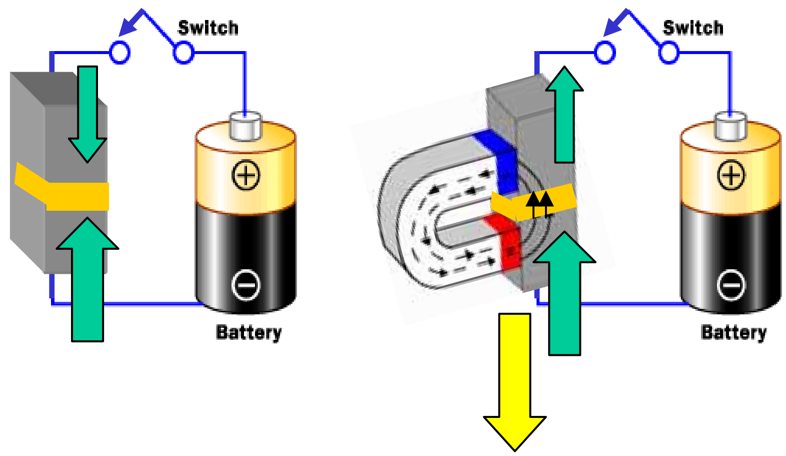


# Diode

classical

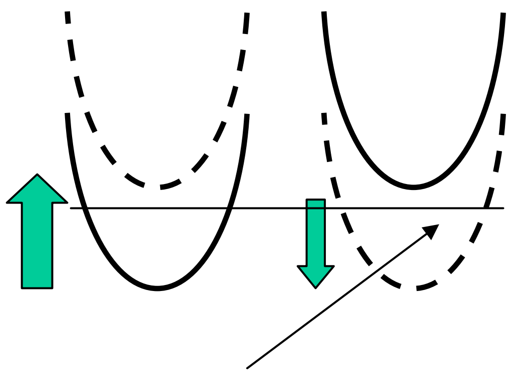



spin-valve

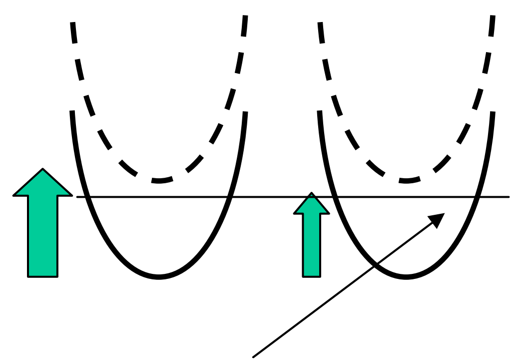



## TMR

## Based on ferromagnetism only

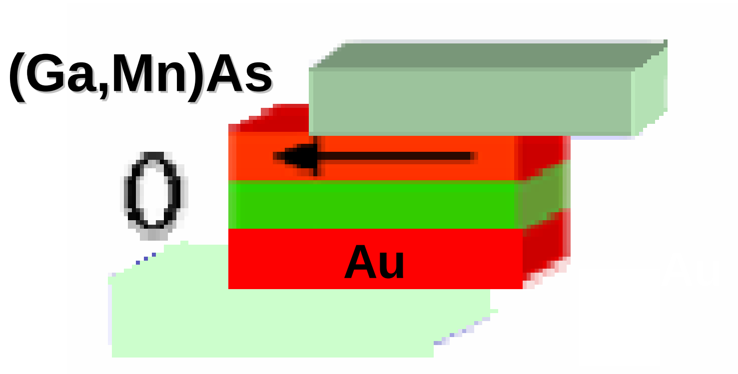


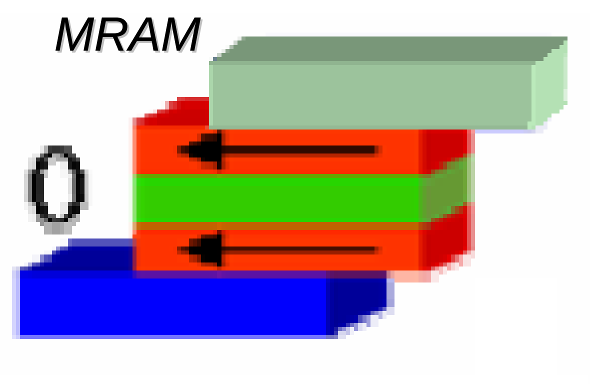
no (few) spin-up DOS available at $E_F$

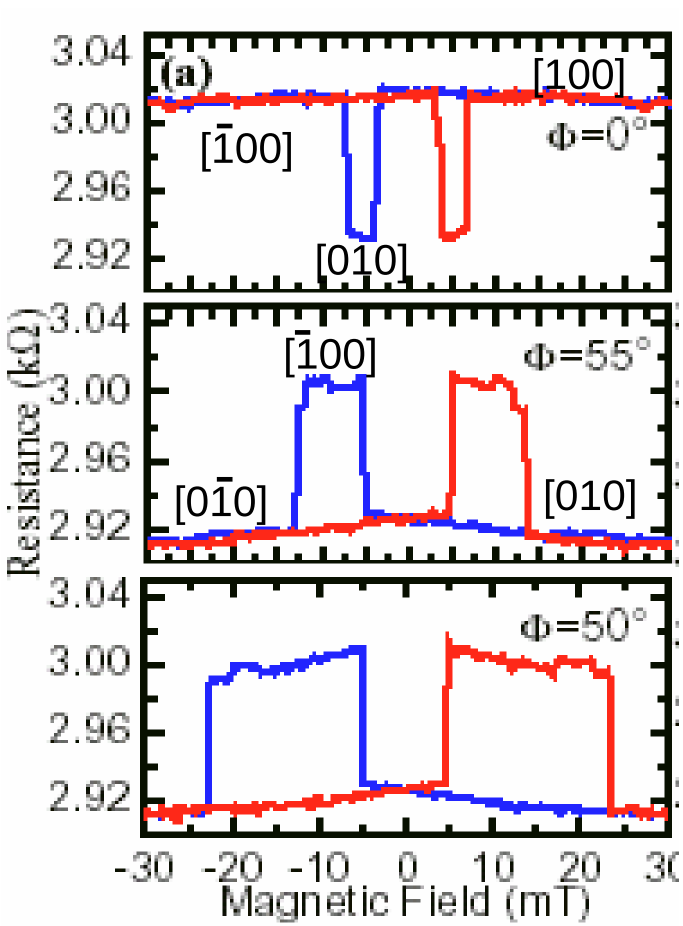


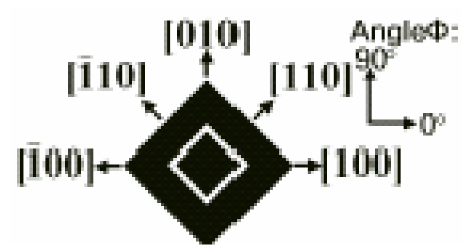
large spin-up DOS available at $E_F$

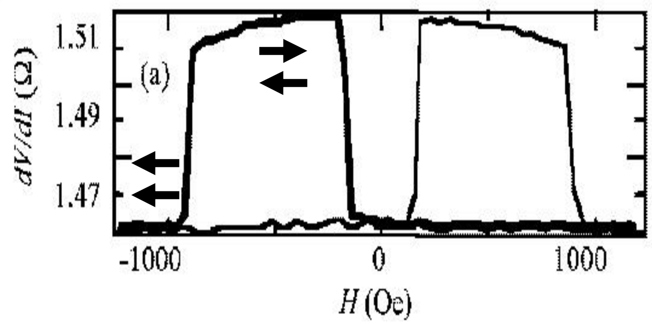
# Tunneling AMR: anisotropic tunneling DOS due to SO-coupling



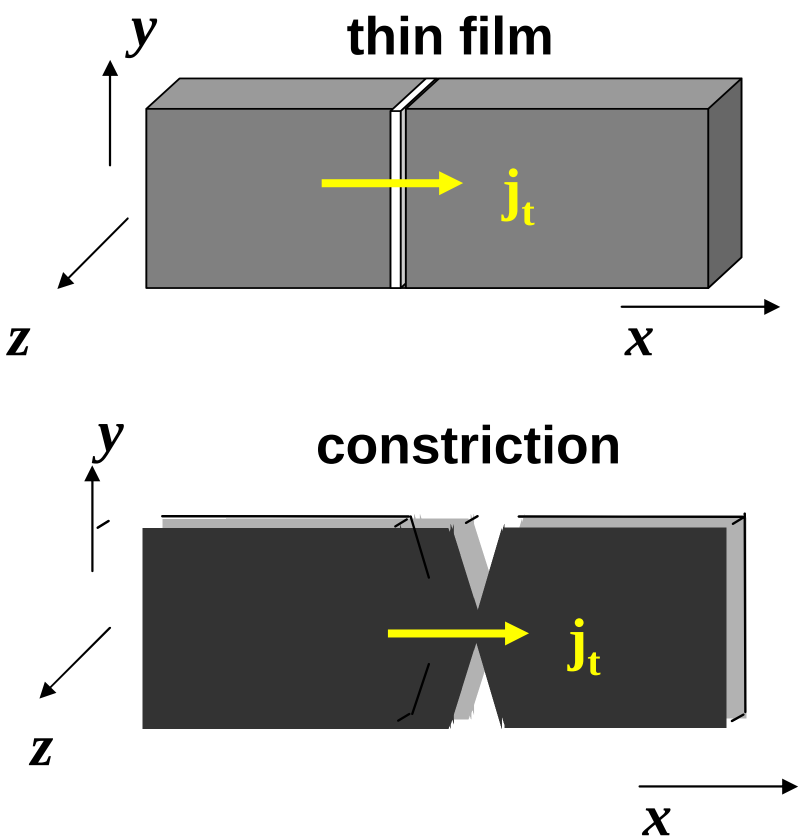

- no exchange-bias needed

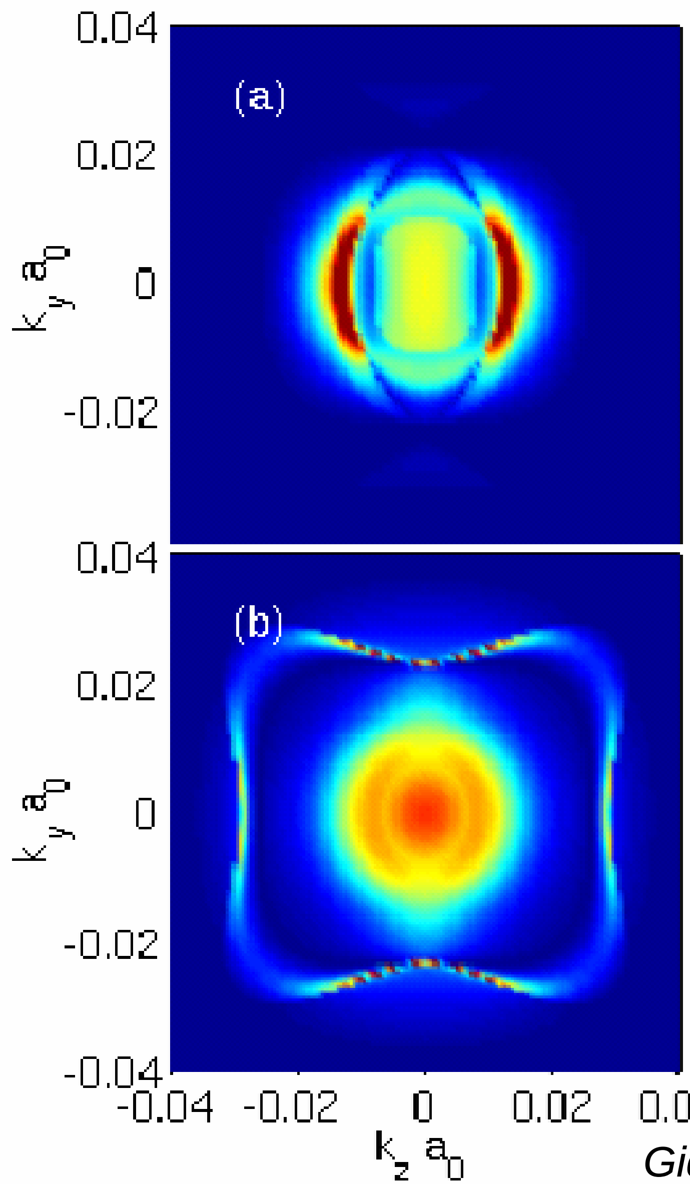
- spin-valve with ritcher phenomenology than TMR

*Gould, Ruster, Jungwirth, et al., PRL '04, '05*

**Wavevector dependent tunnelling probability $T$ ($k_y$, $k_z$) in GaMnAs**

**Red high T; blue low T.**



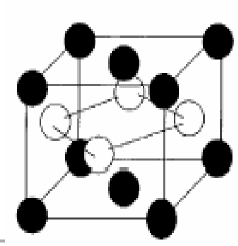




Magnetization perp. to plane

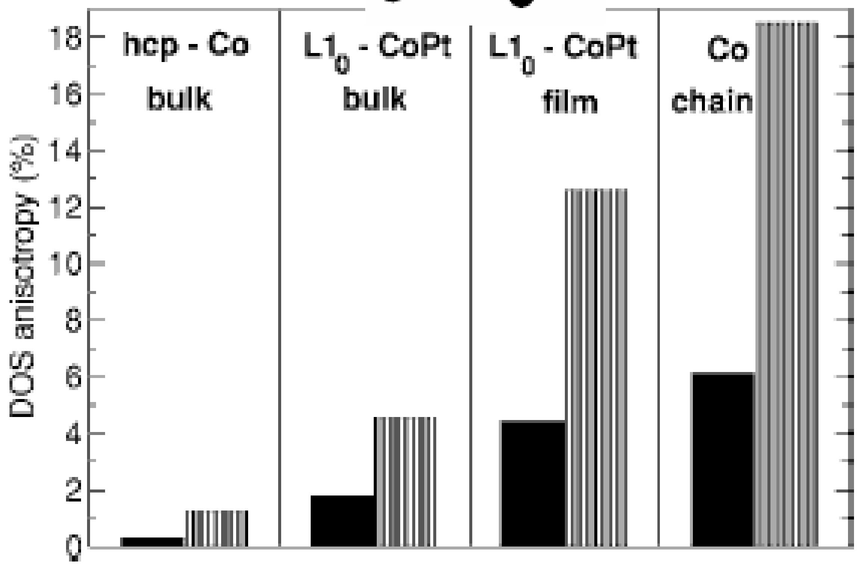
Magnetization in-plane

*Giddings, Khalid, Jungwirth*
*Wunderlich et al., PRL '05*

# TAMR in metals

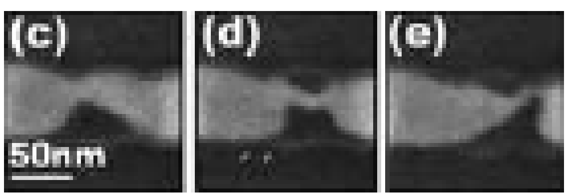


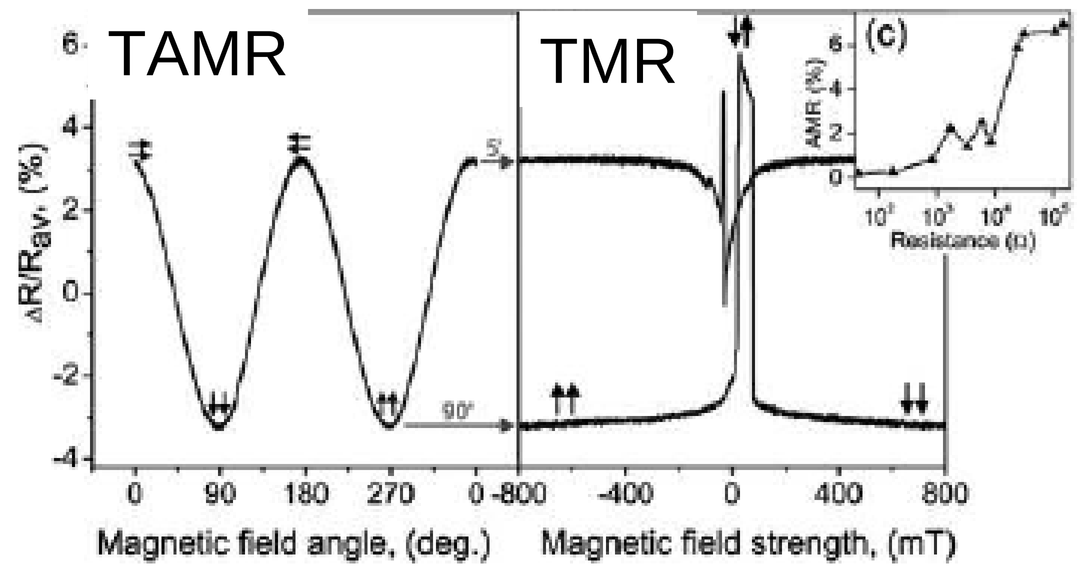
*ab-initio calculations*




*Shick, Maca, Masek, Jungwirth, PRB '06*

NiFe



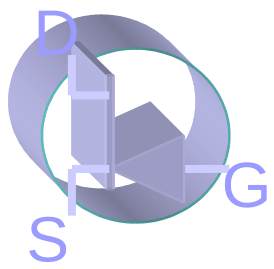




*Bolotin,Kemmeth, Ralph, cond-mat/0602251*

TMR ~TAMR >>AMR

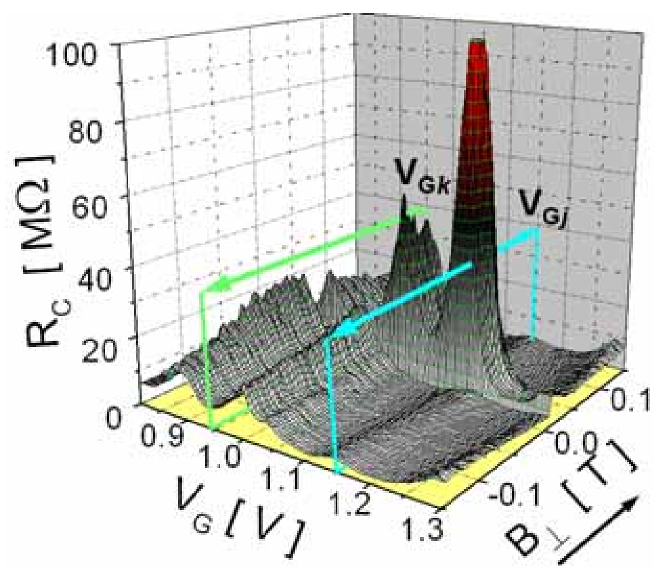
*Viret et al., cond-mat/0602298* Fe, Co break junctions TAMR >TMR

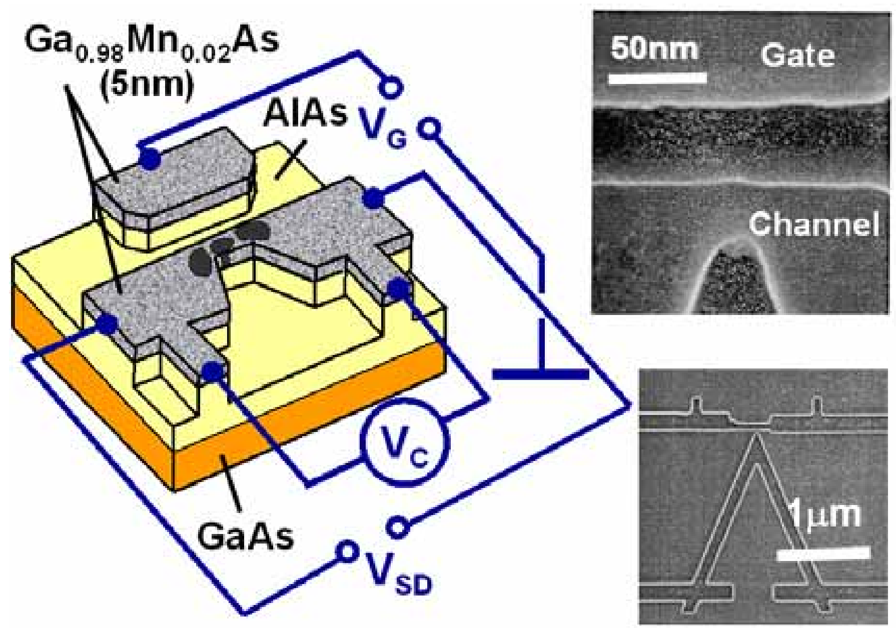
# **Spintronic transistor** - magnetoresistance controlled by gate voltage




Narrow channel & side gate
- to enhance transistor action in this
  highly-doped semiconductor

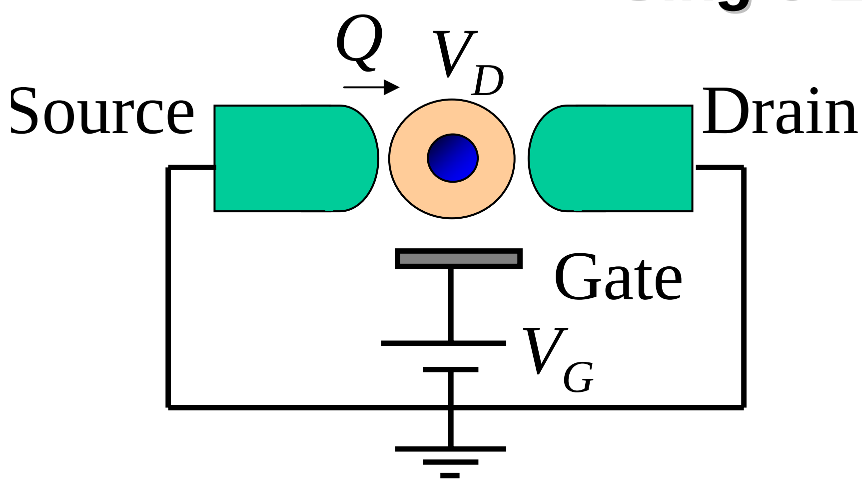
Ferromagnetic semiconductor
- natural choice of material




**Coulomb Blockade AMR: SET & anisotropic chemical potential due to SO-coupling**

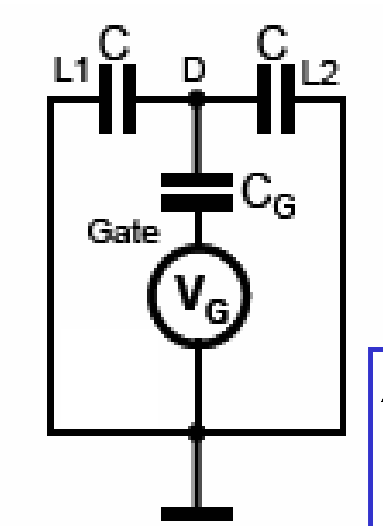
# Single Electron Transistor




- $V_g = 0$

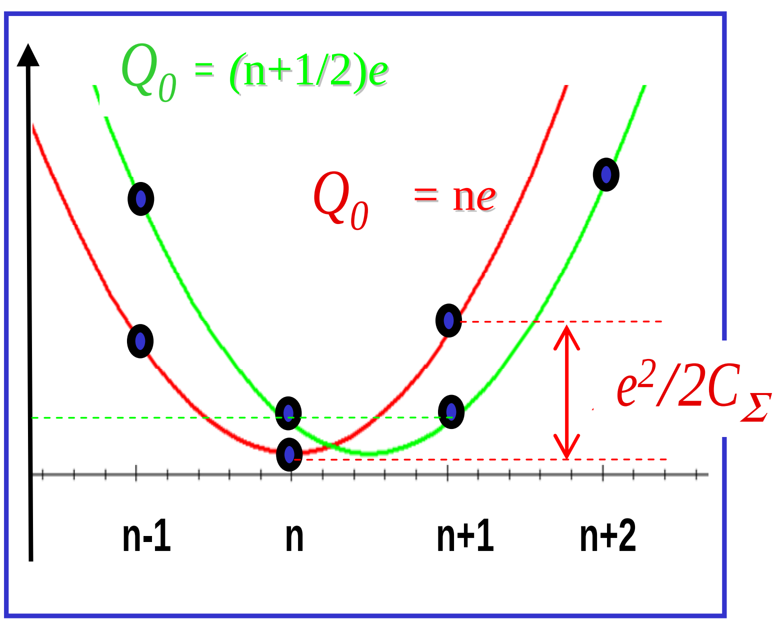
$$U = \int_0^Q dQ' V_D(Q') \& V_D = Q/C_\Sigma \rightarrow U = \frac{Q^2}{2C_\Sigma}$$

$$\frac{e^2}{2C_\Sigma} > k_B T \quad \rightarrow \text{Coulomb blockade}$$




- $V_g \neq 0$

$$U = \frac{(Q+Q_0)^2}{2C_\Sigma} \& Q_0 = C_G V_G$$




$Q = ne$ - discrete

$Q_0 = C_g V_g$ - *continuous*

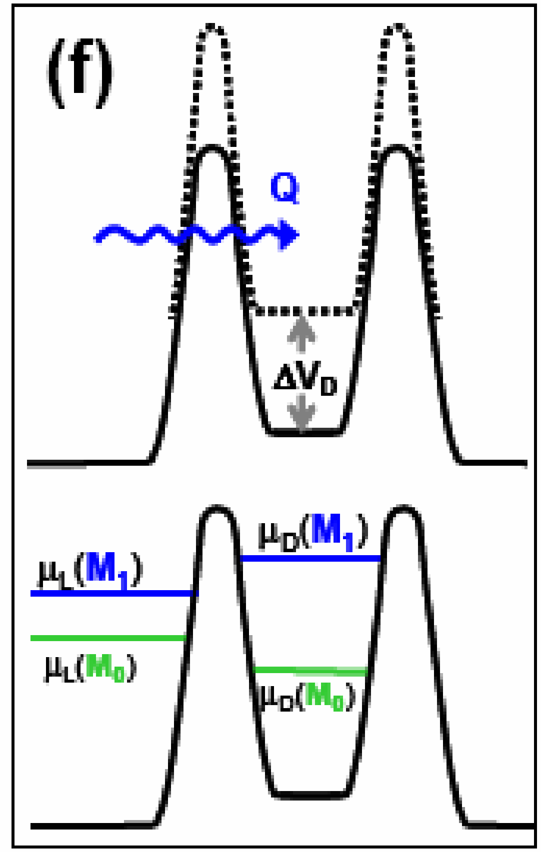
$Q_0 = -ne \rightarrow$ blocked

$Q_0 = -(n+1/2)e \rightarrow$ open

# Coulomb blockade anisotropic magnetoresistance

**Spin-orbit coupling →**

chemical potential depends on $\vec{M}$



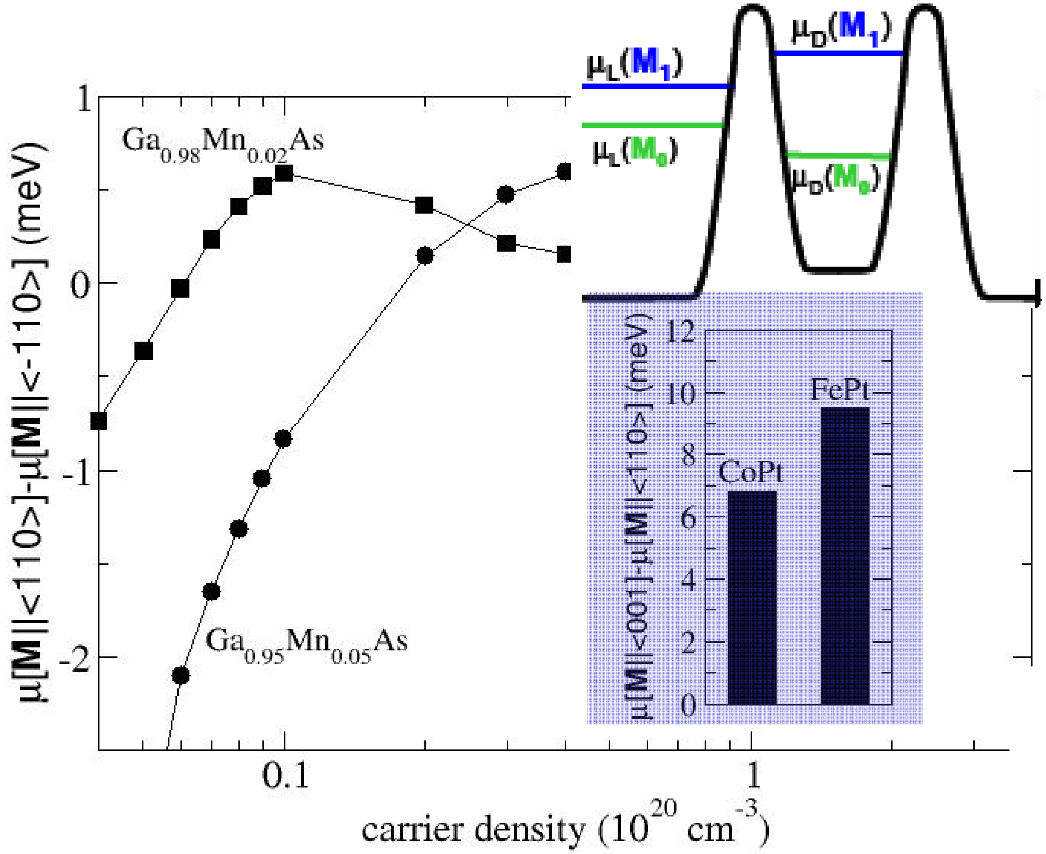

If lead and dot different
(different carrier concentrations in our (Ga,Mn)As SET)

$$U = \int_0^Q dQ' V_D(Q') + \frac{Q\Delta\mu(\vec{M})}{e} \;\&\; \Delta\mu(\vec{M}) = \mu_L(\vec{M}) - \mu_D(\vec{M})$$

$$U = \frac{(Q+Q_0)^2}{2C_\Sigma} \;\&\; Q_0 = C_G[V_G + V_M(\vec{M})] \;\&\; V_M = \frac{\Delta\mu(\vec{M})}{e}\frac{C_\Sigma}{C_G}$$

electric & magnetic

control of Coulomb blockade oscillations



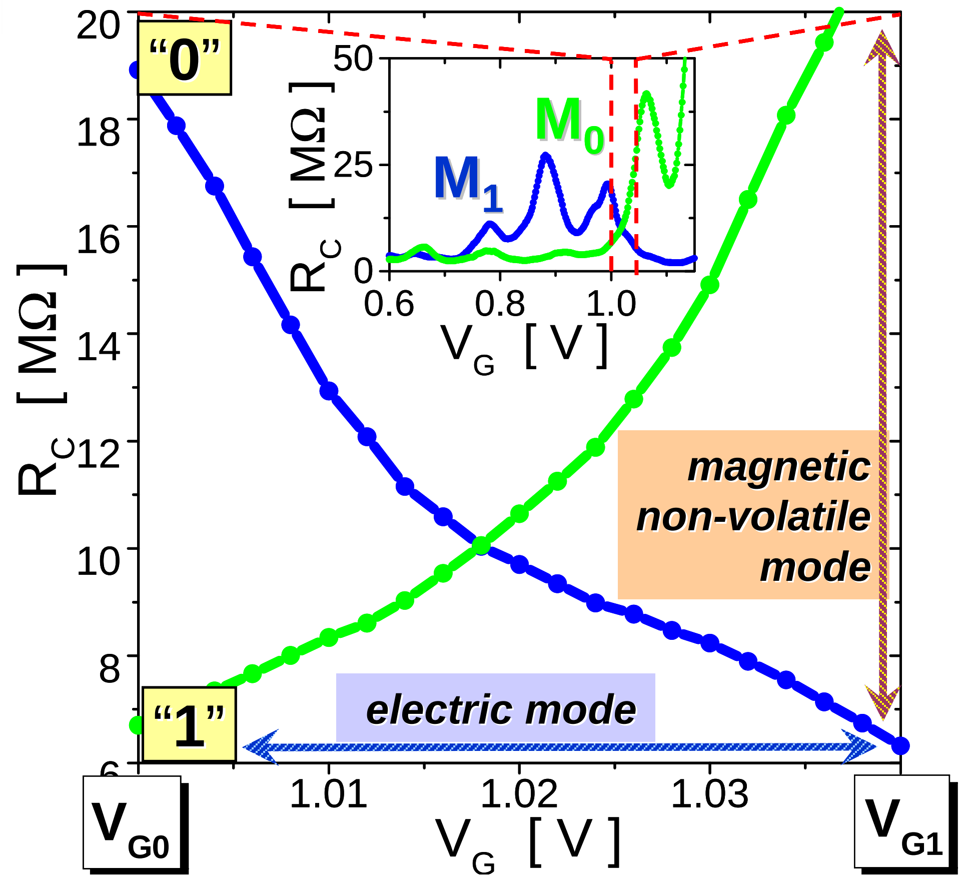

*Wunderlich, Jungwirth, Kaestner, et al., preprint*

- CBAMR if change of $|\Delta\mu(\mathbf{M})| \sim e^2/2C_\Sigma$
- In (Ga,Mn)As ~ meV (~ 10 Kelvin)
- In room-T ferromagnet change o $|\Delta\mu(\mathbf{M})|$~100K

## Programmable logic with CBAMR

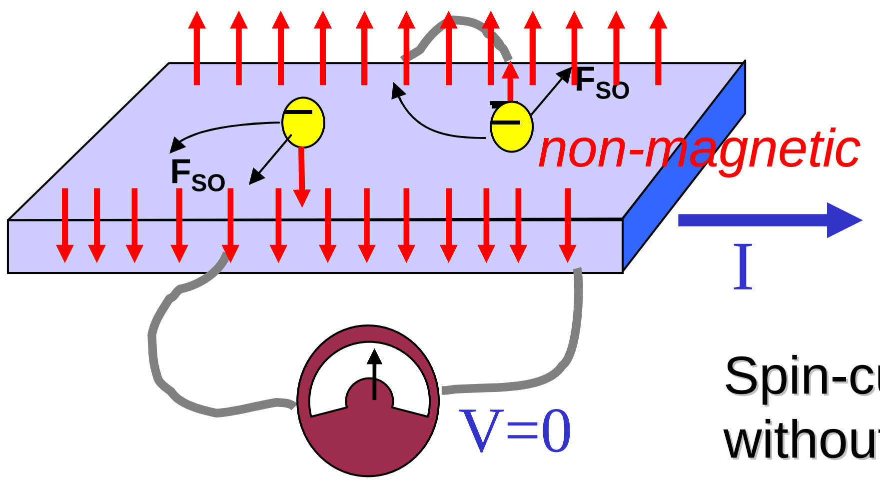
***p*- or *n*-type FET-like transistor**

**in a single nano-sized CBAMR device**



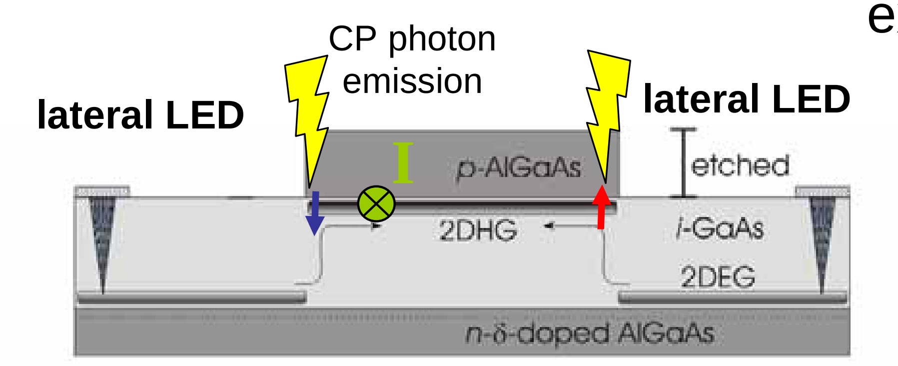
# SPIN HALL EFFECT

no ferromagnetism, spin-orbit coupling only
all-electric spintronics




Spin-current generation in non-magnetic systems without applying external magnetic fields

Spin accumulation without charge accumulation excludes simple electrical detection



## **Intrinsic SHE**: present in perfect crystal and when spin-orbit coupling >> impurity scattering rate

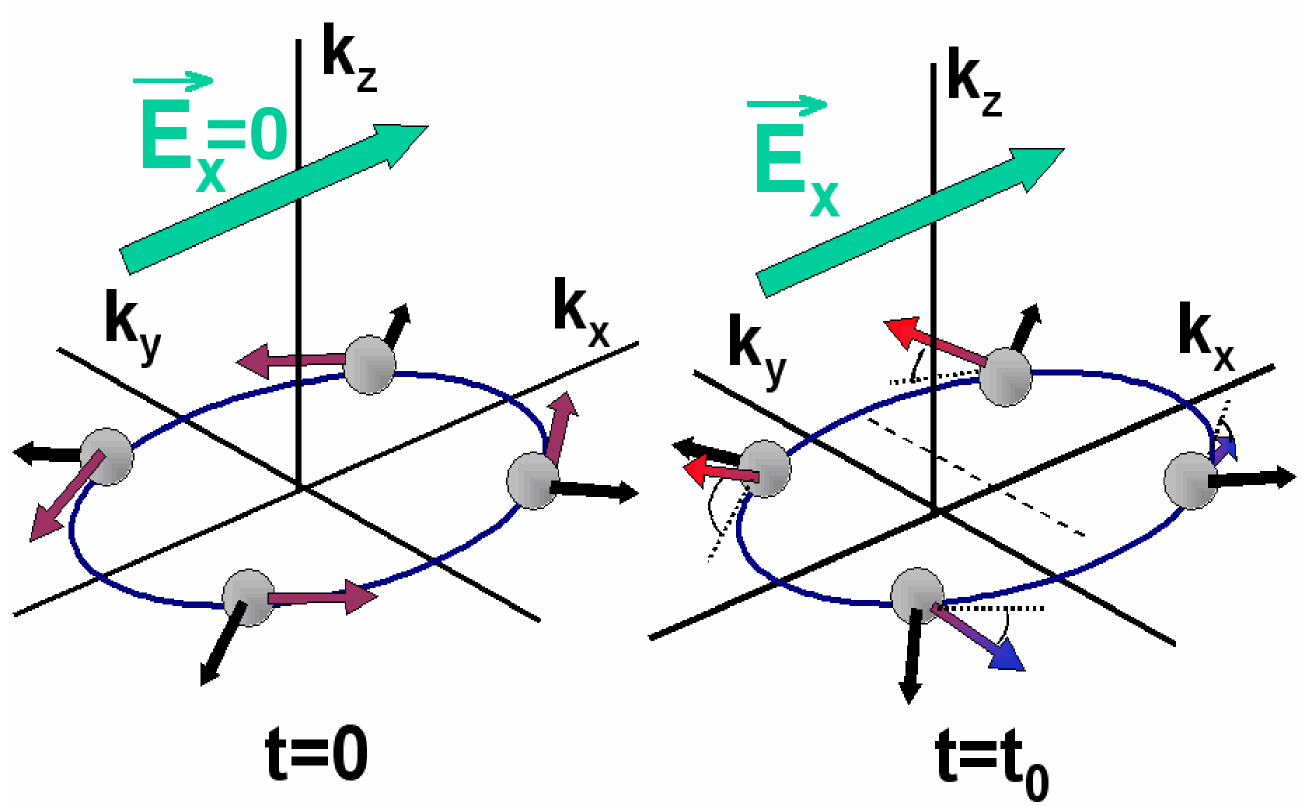
*Murakami, Nagaosa, Zhang, Science '03*

*Sinova, Culcer, Niu, Sinitsyn, Jungwirth, MacDonald, Phys. Rev. Lett. '04*

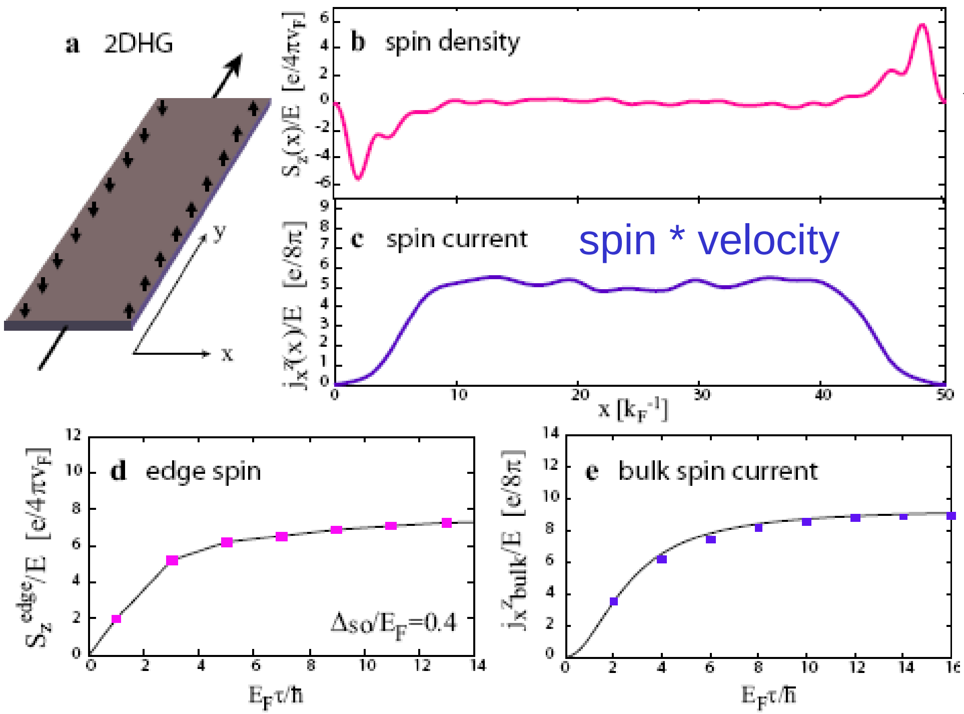
Heuristic picture

$$H_{SO} = \vec{s} \cdot \vec{B}_{eff}$$

$$\vec{B}_{eff} = \frac{1}{2m^2c^2}(\nabla V) \times \vec{p}$$

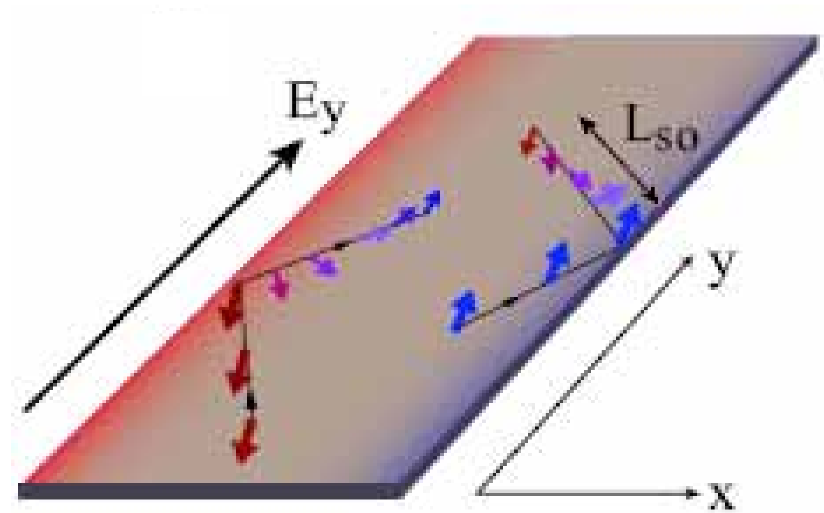


# Microscopic theory and some interpretation




experimentally detected

non-conserving (ambiguous) theoretical quantity




$S^z_{edge}\, L_{so} \sim j^z_{bulk}\, t_{so}$

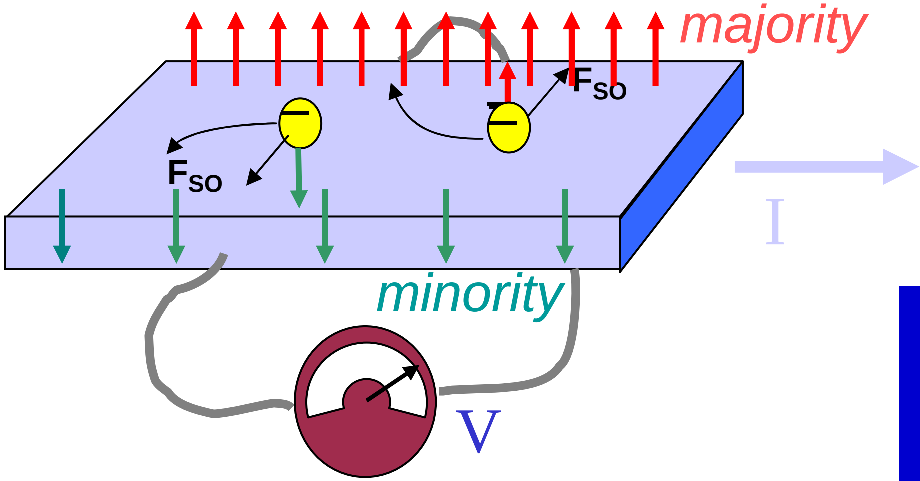
*Nomura, Wunderlich, Sinova, Kaestner, MacDonald, Jungwirth, Phys. Rev. B '05*

$t_{so}=h/\Delta_{so}$ : (intrinsic) spin-precession time

$L_{so}=v_F\, t_{so}$ : spin-precession length

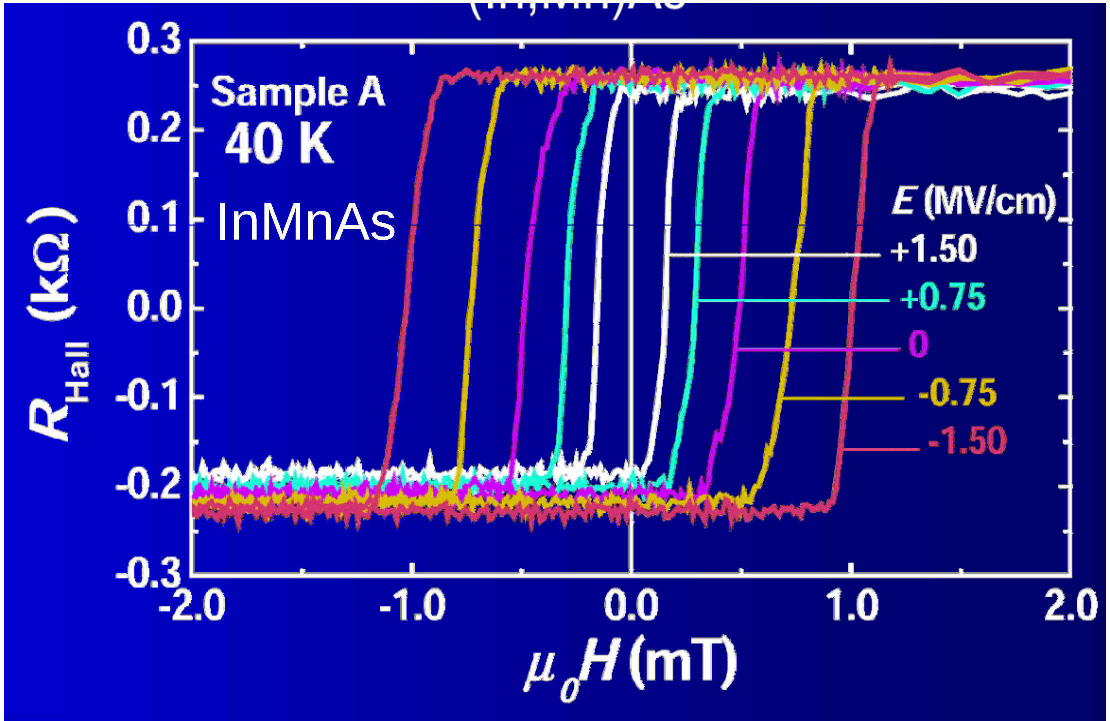
# Spin and Anomalous Hall effects

*Spin-orbit coupling "force" deflects **like-spin** particles*




$$\rho_H = R_0 B + 4\pi R_s M$$

Simple electrical measurement of magnetization



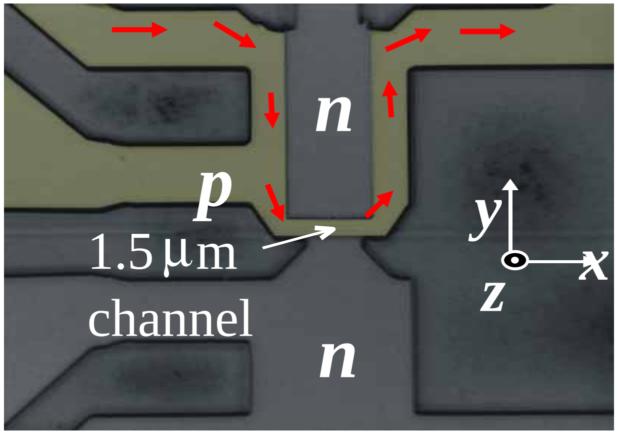

D. Chiba *et al.*, Science **301**, 943 (2003)

# Intrinsic AHE approach explains many experiments

- (Ga,Mn)As systems *[Jungwirth et al. PRL 02, APL 03, Chun et al. cond-mat/0603808]*
- Fe *[Yao, Kleinman, MacDonald, Sinova, Jungwirth et al PRL 04*]
- Co *[Kotzler and Gil PRB 05]*
- Layered 2D ferromagnets such as SrRuO3 and pyrochlore ferromagnets *[Onoda and Nagaosa, J. Phys. Soc. Jap. 01,Taguchi et al., Science 01, Fang et al Science 03, Shindou and Nagaosa, PRL 01]*
- Ferromagnetic spinel CuCrSeBr *[Lee et al. Science 04]*

# Spintronics with spin-orbit coupling

- New effects and rich phenomenology (TAMR,CBAMR)
- As strong effects as effects based on FM only
- p-type (Ga,Mn)As ideal systems - better understanding of old effects (AMR, AHE), searching for new generic effects
- Spintronic transistors (CBAMR-SET) and spin generation and manipulation with electric fields only (SHE)




SHE microchip, 100μA

high-field lab. equipment
100 A