Ferromagnetic semiconductor (Ga,Mn)As:

Electronic and magnetic structure, spin-dependent phenomena and device concepts

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TJ, Jairo Sinova, J. Mašek, J. Kučera, A.H. MacDonald, ***Rev. Mod. Phys. 78, 809 (2006)***

K. Sato, L. Bergqvist, J. Kudrnovský, P. H. Dederichs, O. Eriksson, I. Turek, B. Sanyal, G. Bouzerar, H. Katayama-Yoshida, V. A. Dinh, T. Fukushima, H. Kizaki, and R. Zeller, ***Rev. Mod. Phys. 82, 1633 (2010)***

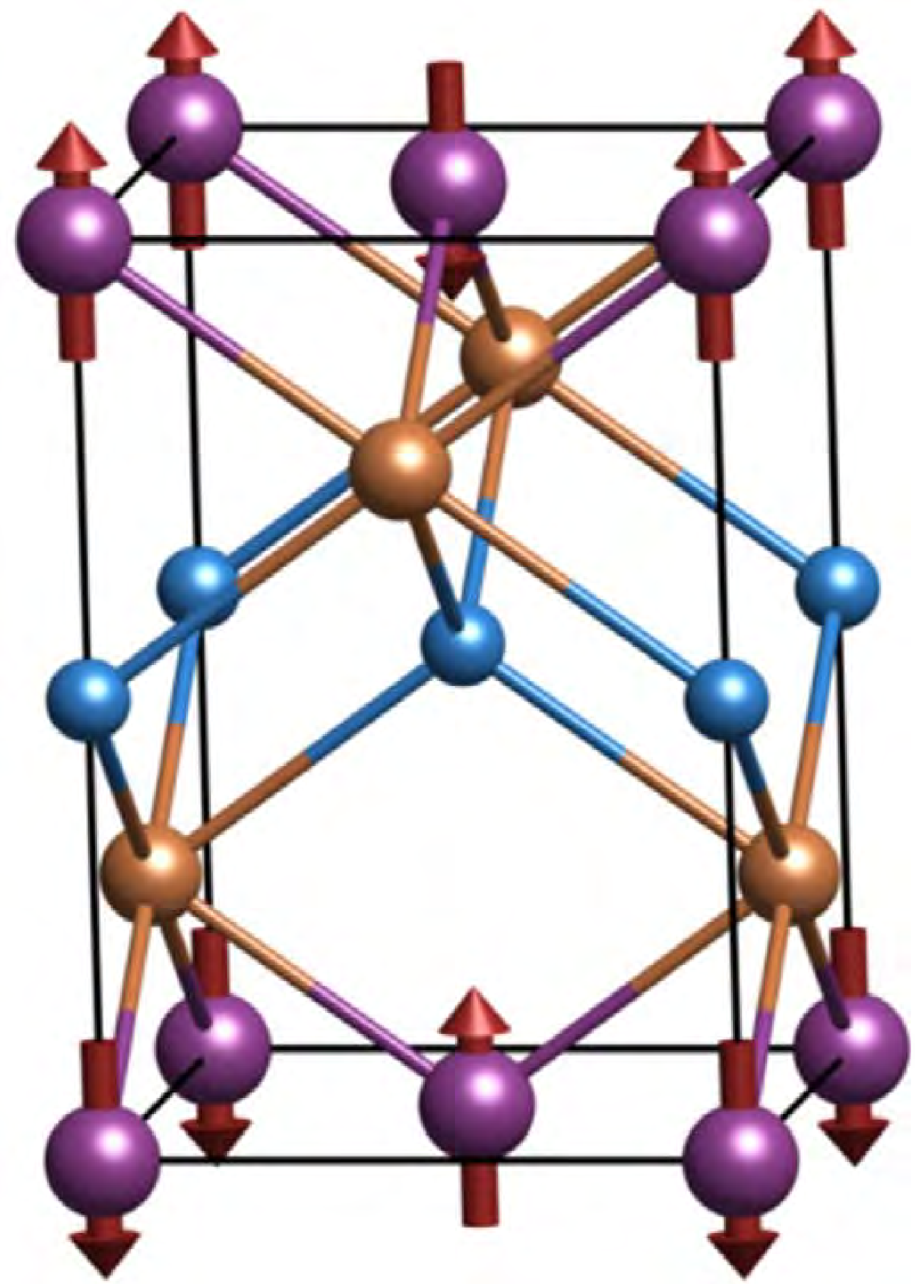
T. Dietl and H. Ohno, ***Rev. Mod. Phys. 86, 187 (2014)***

TJ, J. Wunderlich, V. Novak, K. Olejnik, B. L. Gallagher, R. P. Campion, K. W. Edmonds, A. W. Rushforth, A. J. Ferguson, and P. Nemec, ***Rev. Mod. Phys. 86, 855 (2014)***

Dense-moment intrinsic magnetic semiconductors

more AFMs than FMs and high-T_N in AFMs

LiMnAs



III-V	FM T_C (K)	AFM T_N (K)
FeN		100
FeP		115
FeAs		77
FeSb		100-220
GdN	72	
GdP		15
GdAs		19
GdSb		27
II-V-IV-V	**FM T_C (K)**	**AFM T_N (K)**
$MnSiN_2$		**490**
I-II-V	**FM T_C (K)**	**AFM T_N (K)**
Ia=Li, Na,.. Ib=Cu II=Mn V=Sb,As, P		**> room T**

TJ et al. PRB'11, Cava Physics '11

Dense-moment intrinsic magnetic semiconductors

more AFMs than FMs and high-T_N in AFMs

II-VI	FM T_C (K)	AFM T_N (K)
MnO		122
MnS		152
MnSe		173
MnTe		**323**
EuO	67	
EuS	16	
EuSe		5
EuTe		10

I-VI-III-VI	FM T_C (K)	AFM T_N (K)
$CuFeO_2$		11
$CuFeS_2$		**825**
$CuFeSe_2$		70
$CuFeTe_2$		254

III-V	FM T_C (K)	AFM T_N (K)
FeN		100
FeP		115
FeAs		77
FeSb		100-220
GdN	72	
GdP		15
GdAs		19
GdSb		27

II-V-IV-V	FM T_C (K)	AFM T_N (K)
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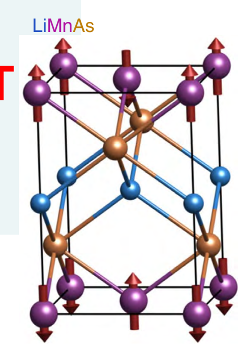
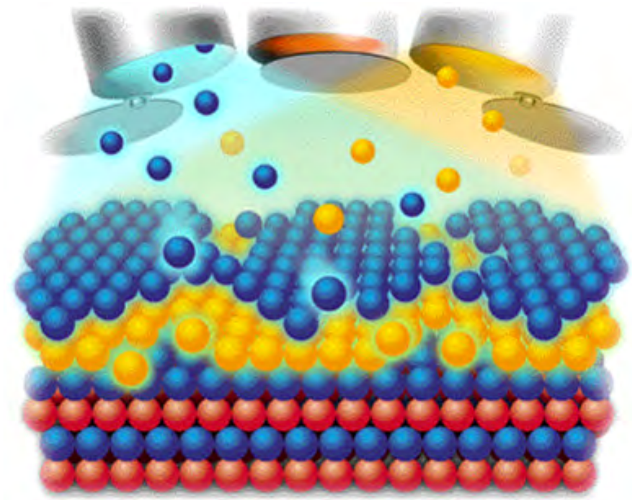
I-II-V	FM T_C (K)	AFM T_N (K)
Ia=Li, Na,.. Ib=Cu II=Mn V=Sb,As, P		**> room T**



TJ et al. PRB'11, Cava Physics '11

Magnetically-doped semiconductors

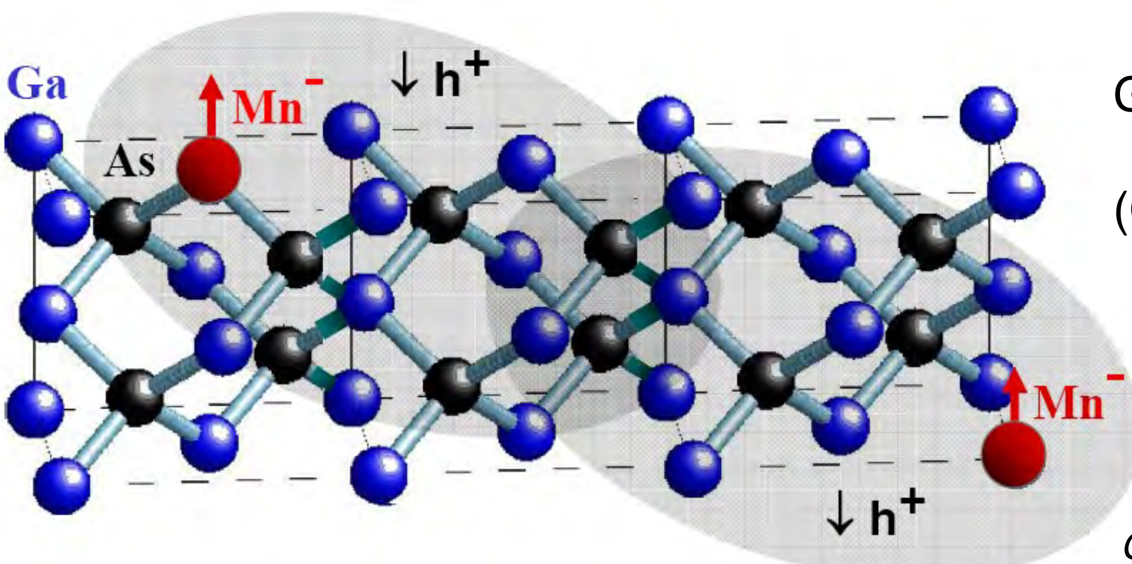
Molecular beam epitaxy of (Ga,Mn)As



GaAs – common III-V semiconductor

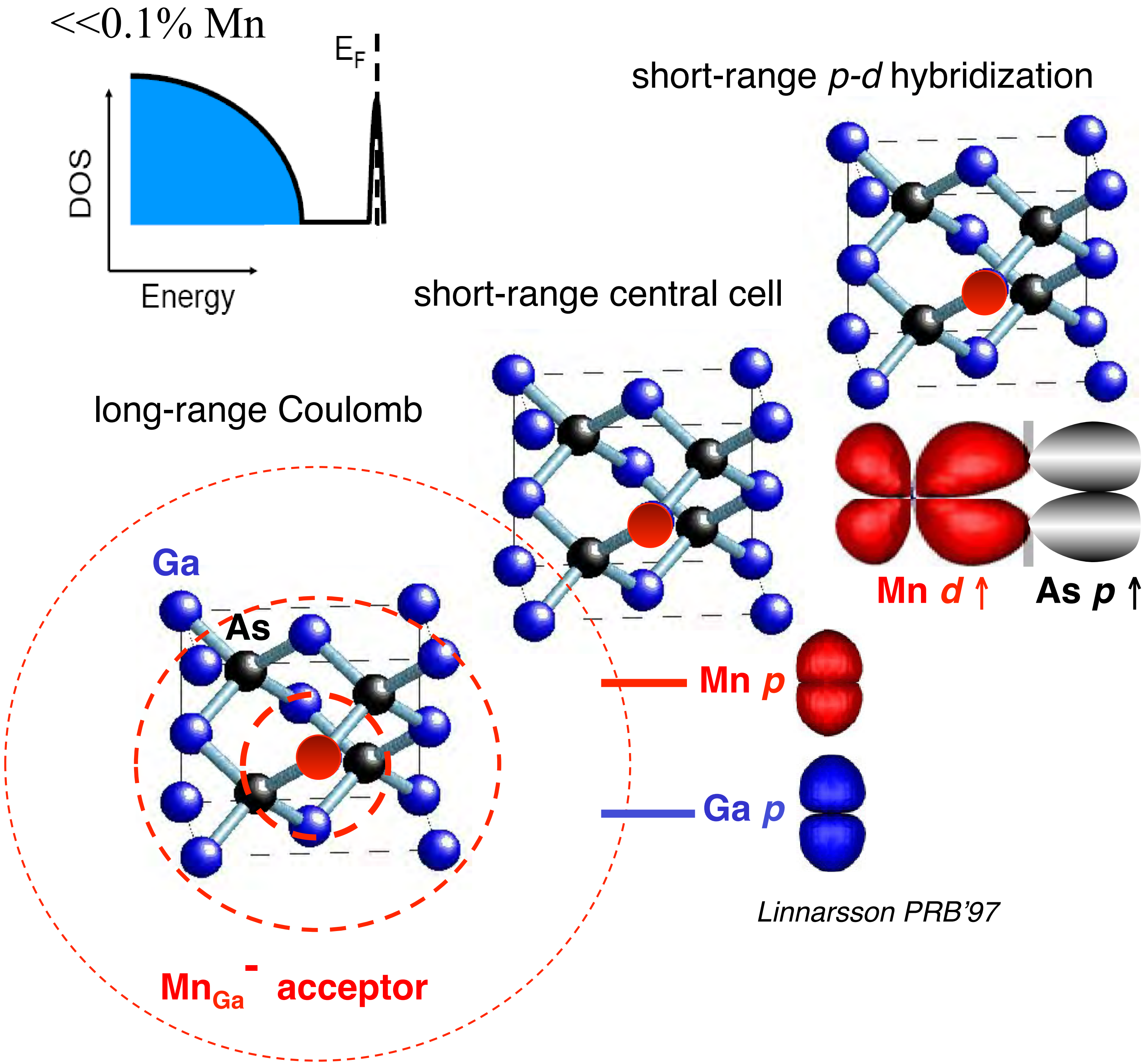
Group-II Mn – magnetic moment, hole

(Ga,Mn)As – feromagnetic semiconductor



Ohno Science '98

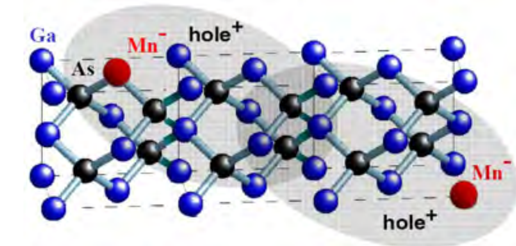
FM (Ga,Mn)As doped semiconductor

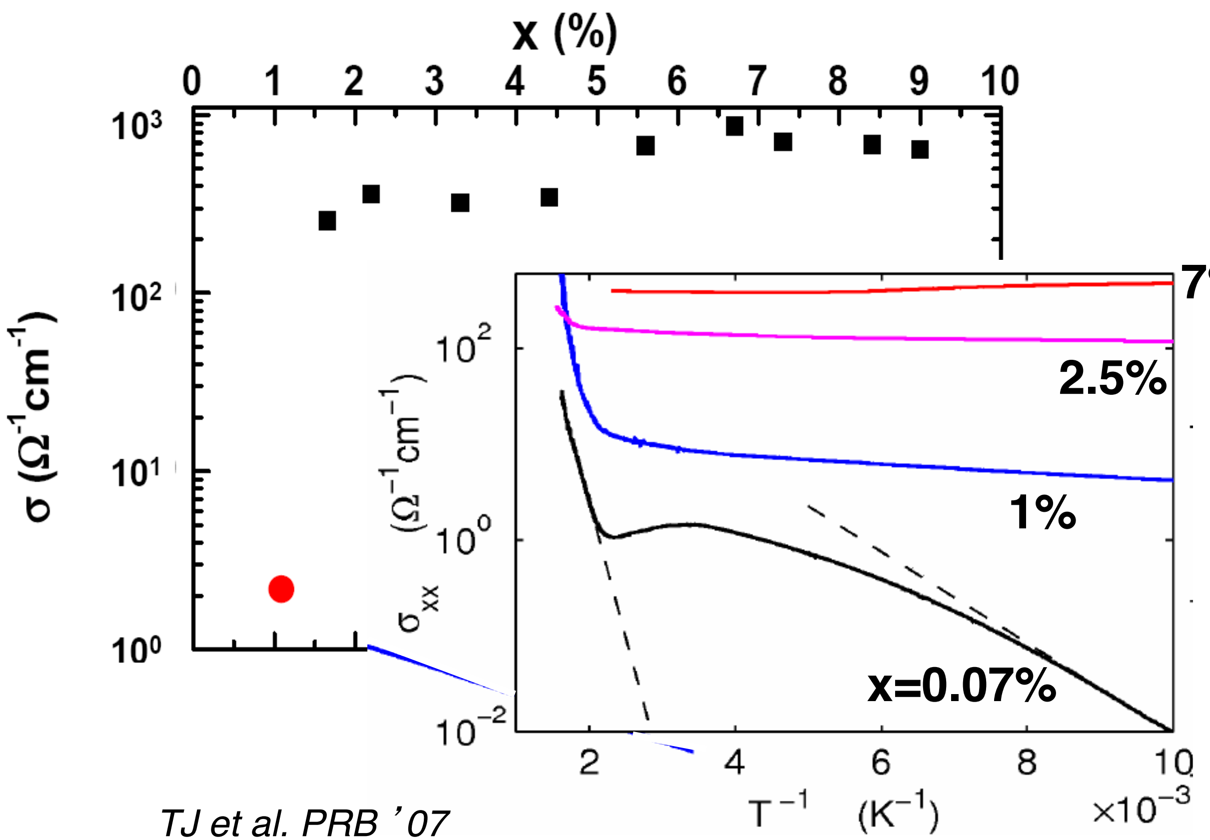


Linnarsson PRB'97

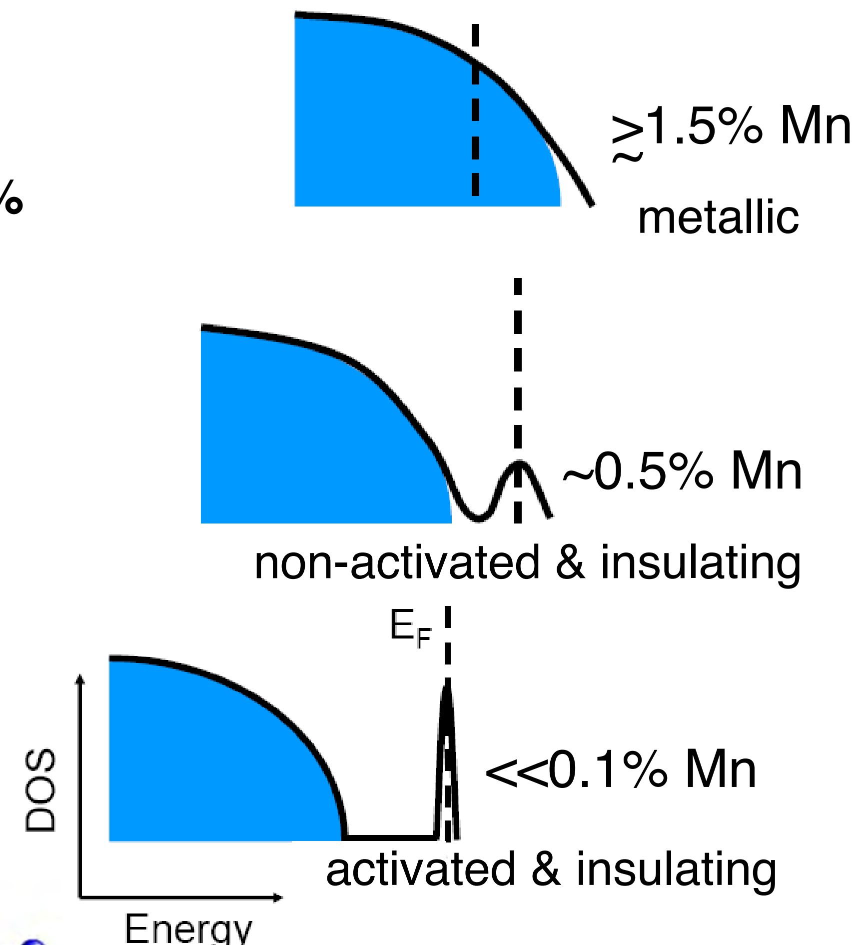
FM (Ga,Mn)As doped semiconductor

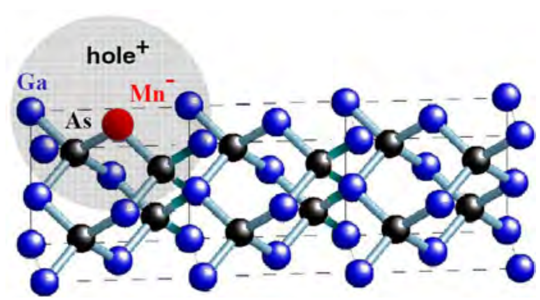
MIT reminiscent of p-GaAs:Zn





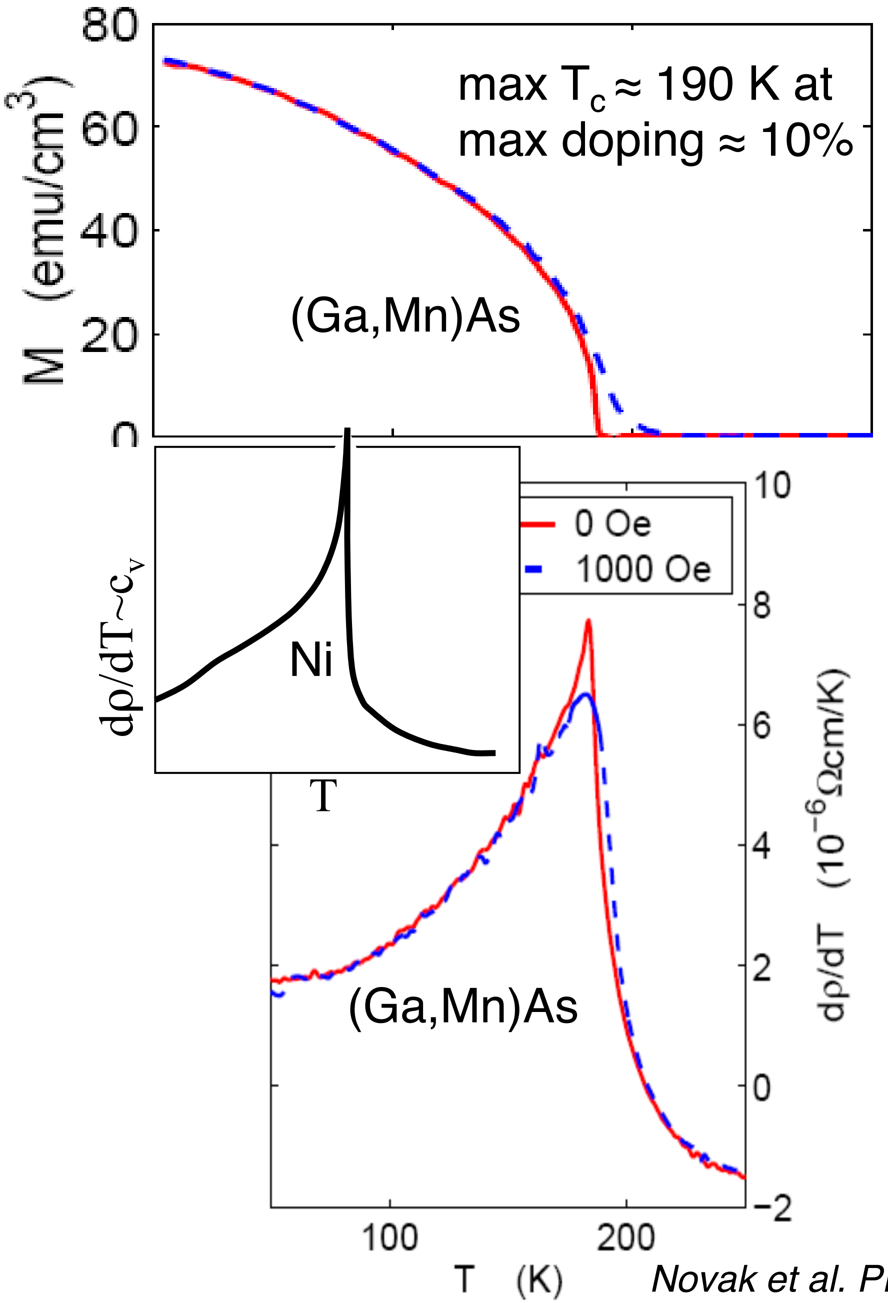
TJ et al. PRB ’07



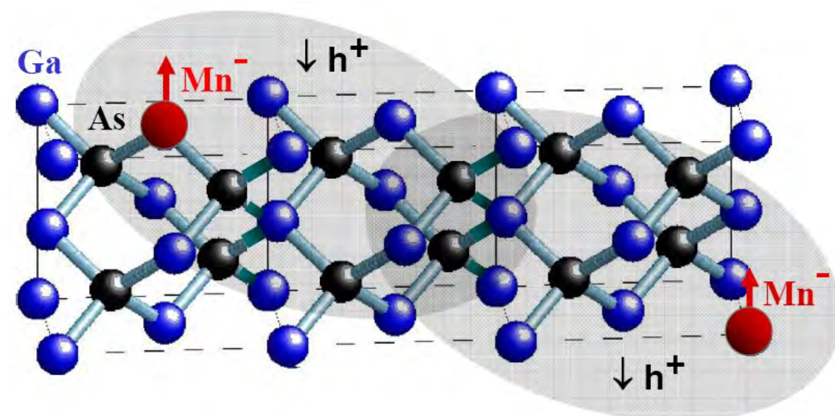


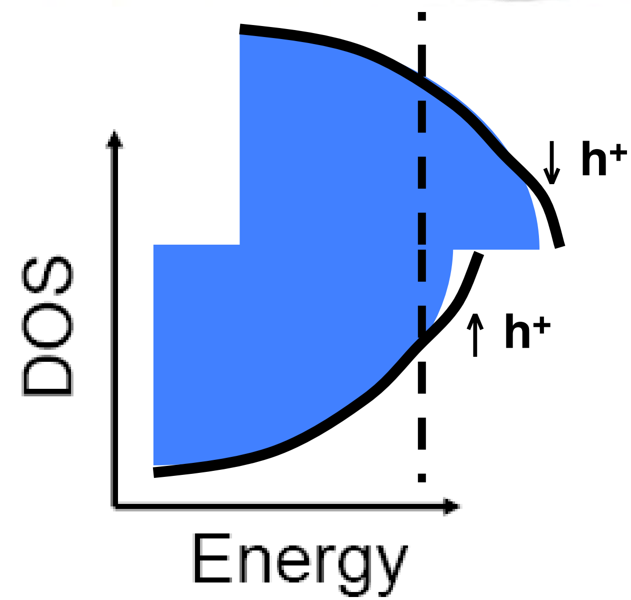
FM (Ga,Mn)As doped semiconductor

Ferromagnetically split itinerant bands reminiscent of conventional FMs Fe, Co, Ni,..



Novak et al. PRL '08

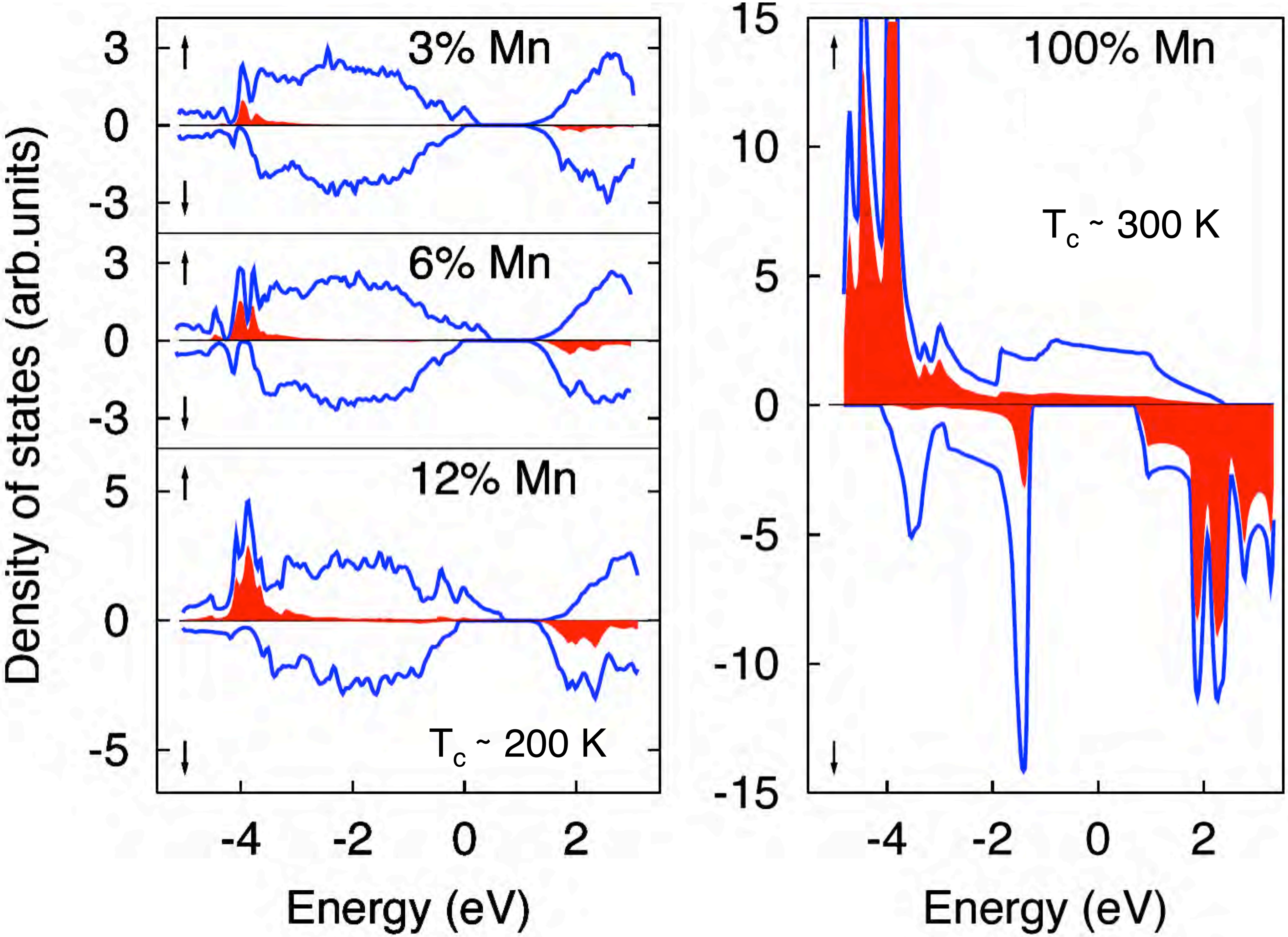




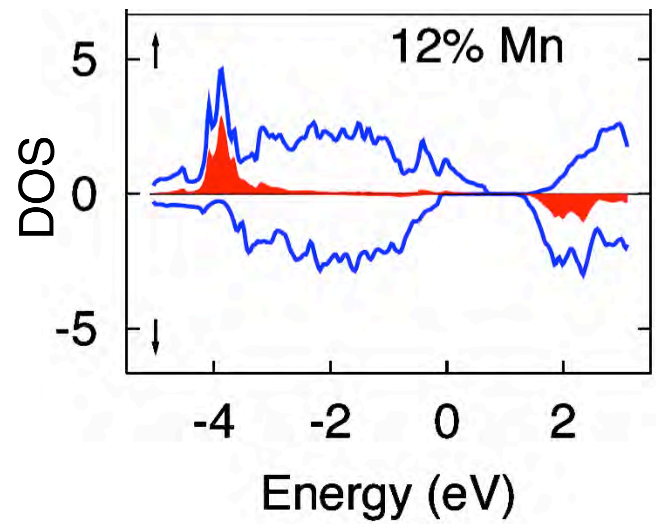
$\gtrsim$1% Mn ferro & insulating

$\gtrsim$1.5% Mn ferro & metallic

From FM (Ga,Mn)As doped semiconductor to FM MnAs metal (wurtzite or ZB-inclusions)



Mn in III-V's: carrier – local moment (Kondo or "s-d") coupling

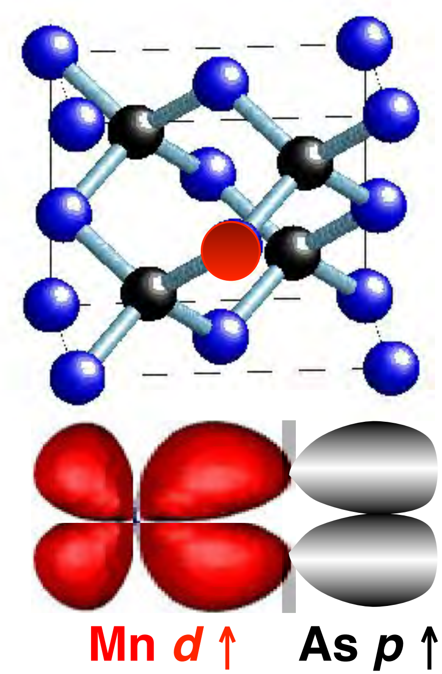


Microscopic Tight-Binding Anderson (TBA) model

$$H_A = \sum_{k,s} \epsilon_k n_{ks} + \sum_s \epsilon_d n_{ds} + U n_{d\uparrow} n_{d\downarrow} + \sum_{ks} (V_{kd} c^\dagger_{ks} c_{ds} + c.c.)$$

Weak-hybridization → Schrieffer-Wolf transformation

p-d hybridization



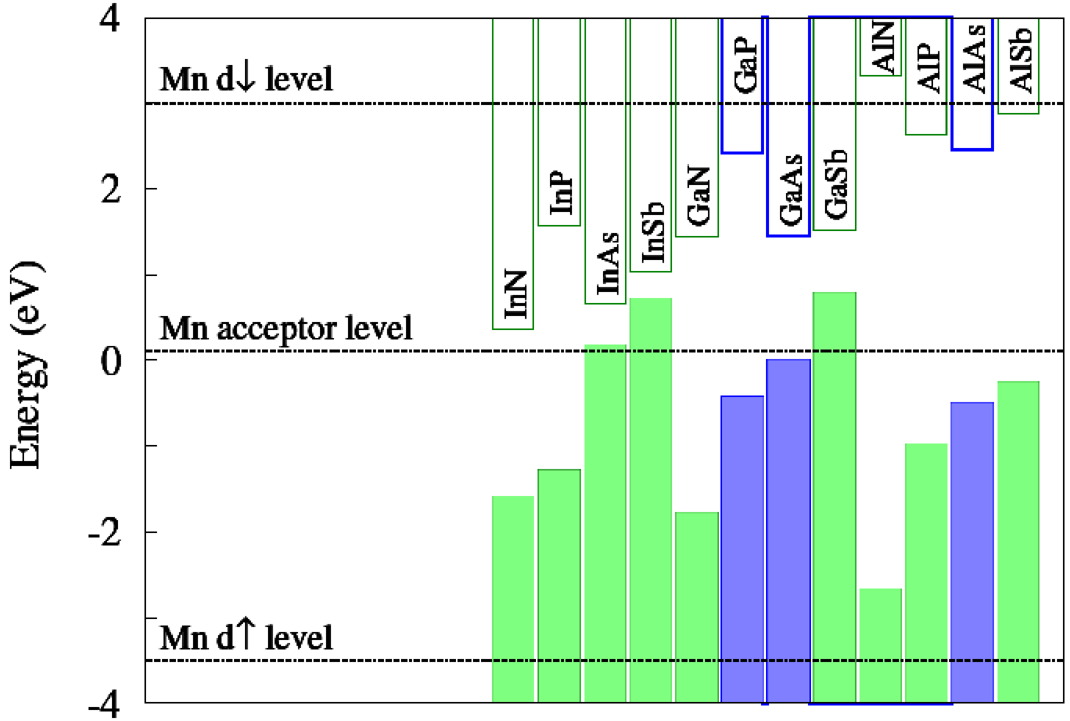
Zener kinetic-exchange model

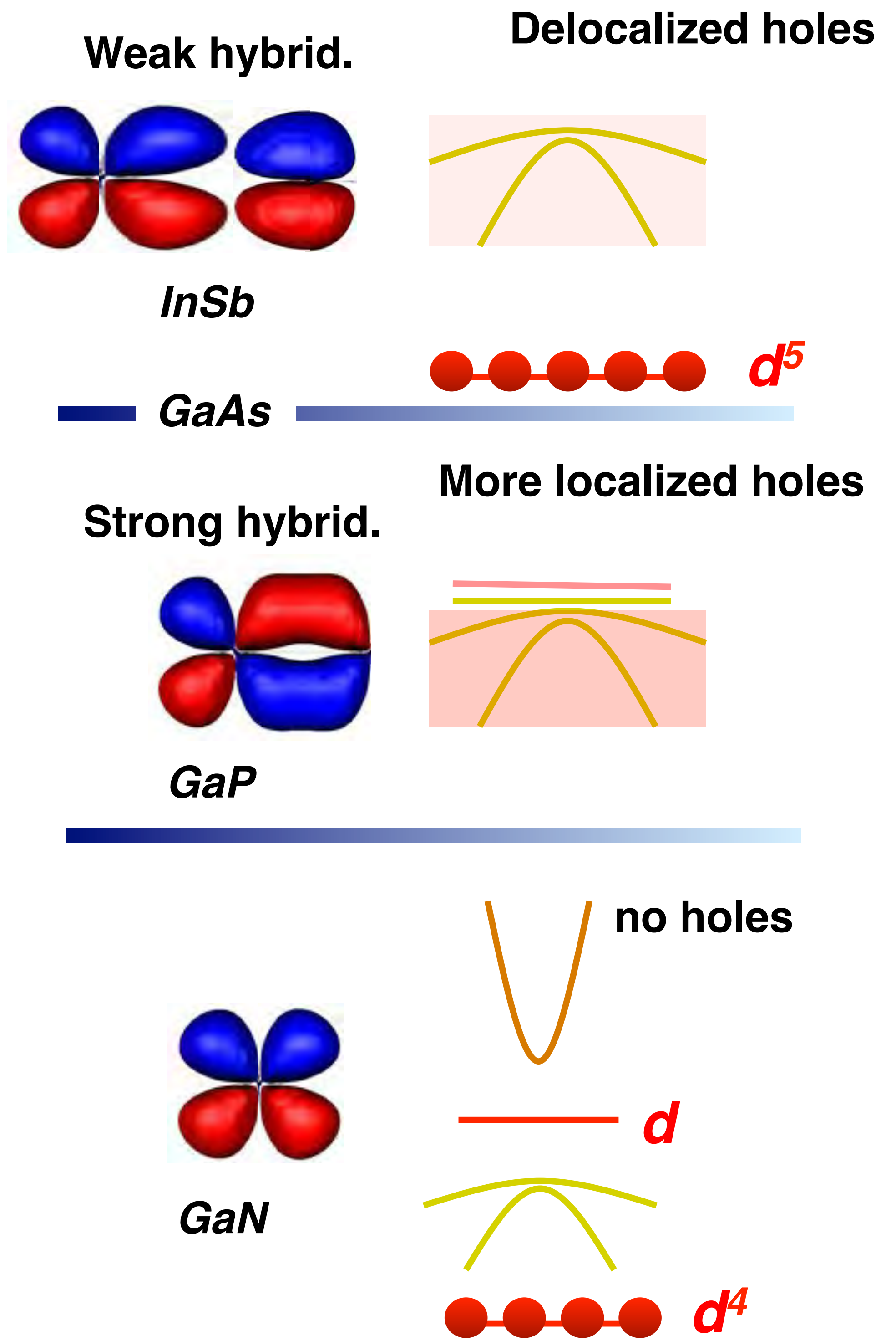
$$J_0 \mathbf{s}_d \cdot \mathbf{s}_{k=0} \qquad J_0 = 2|V_{pd}|^2 \left(\frac{1}{\epsilon_d + U} - \frac{1}{\epsilon_d} \right)$$

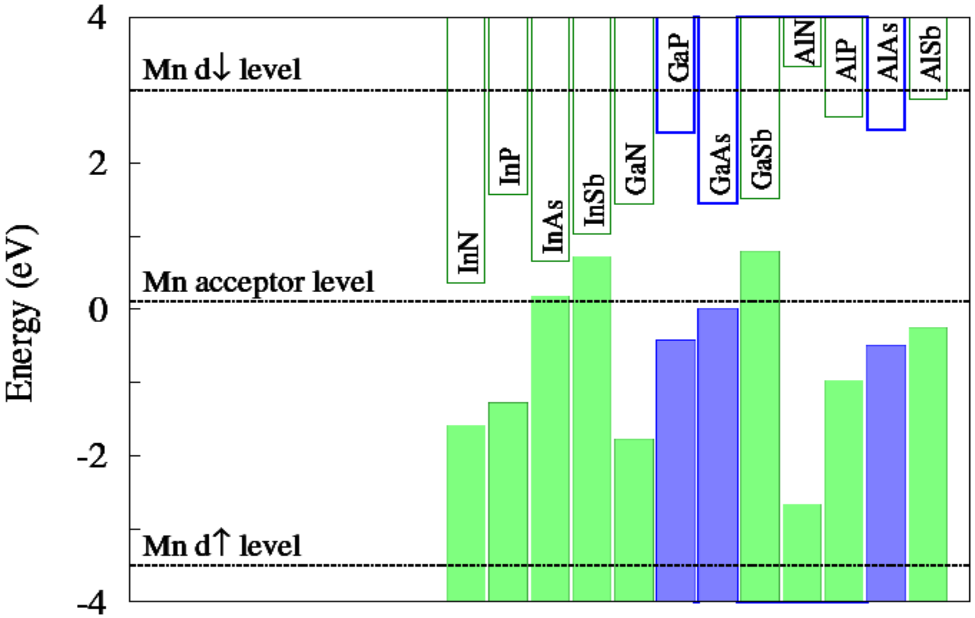
TJ et al., Rev. Mod. Phys. '06

Other (III,Mn)V's

Kudrnovsky et al. PRB 07

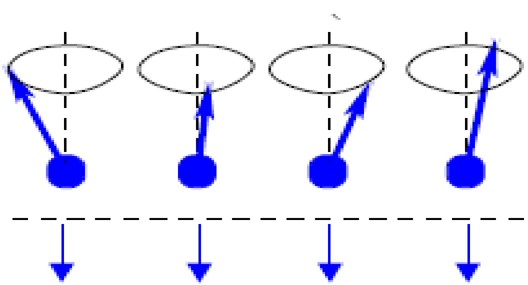






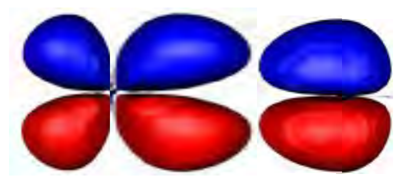
Other (III,Mn)V's DMSs

Kudrnovsky et al. PRB 07



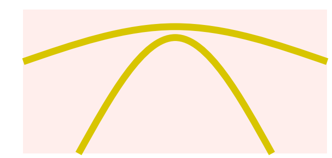
Mean-field but low T_c^{MF}

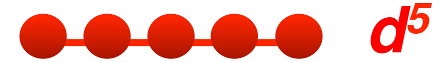
Weak hybrid.



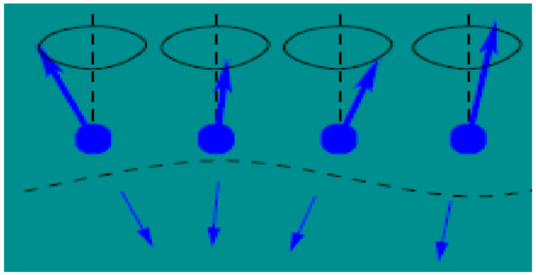
InSb

Delocalized holes



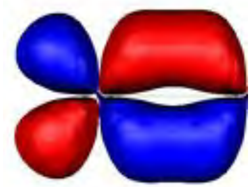


Moderate hybrid. *GaAs*: close to optimal



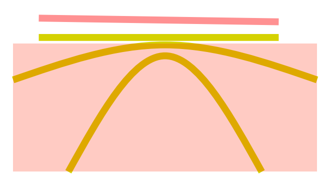
Large T_c^{MF} but low stiffness

Strong hybrid.



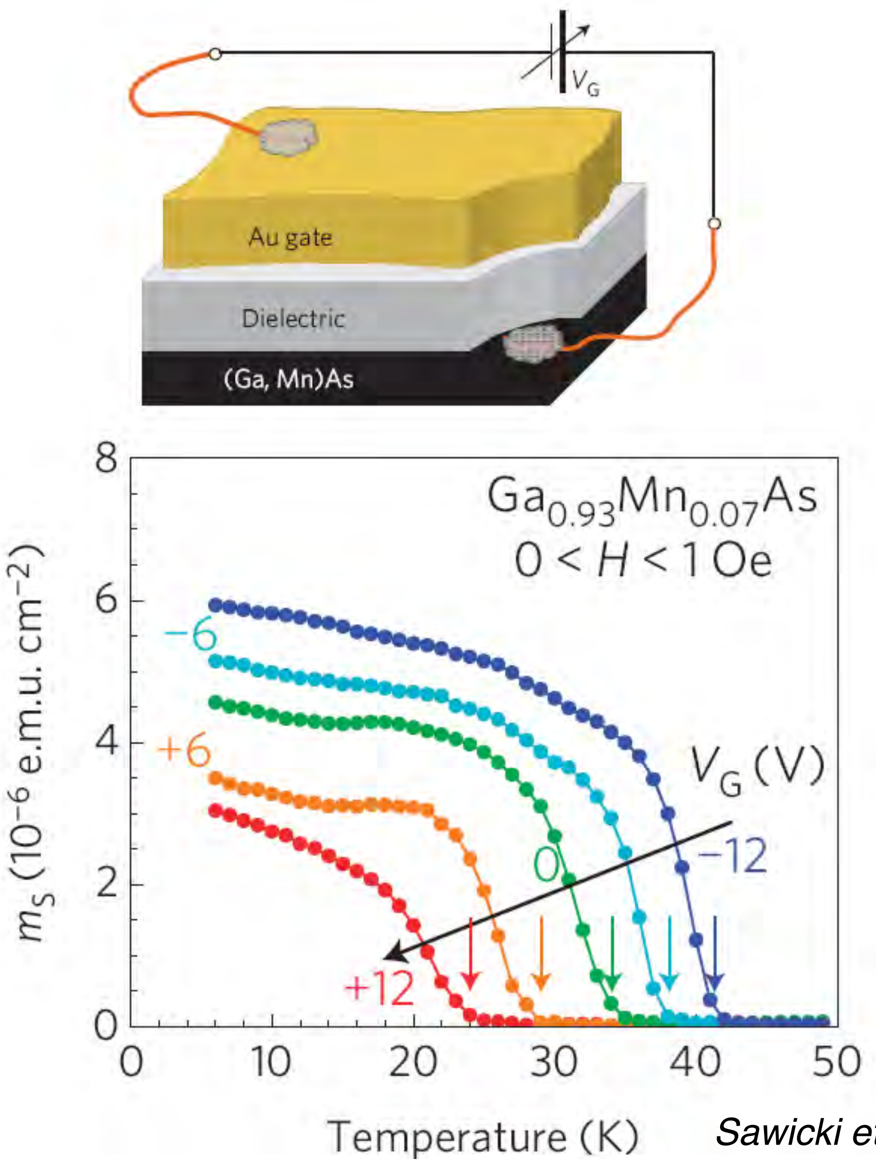
GaP

More localized holes

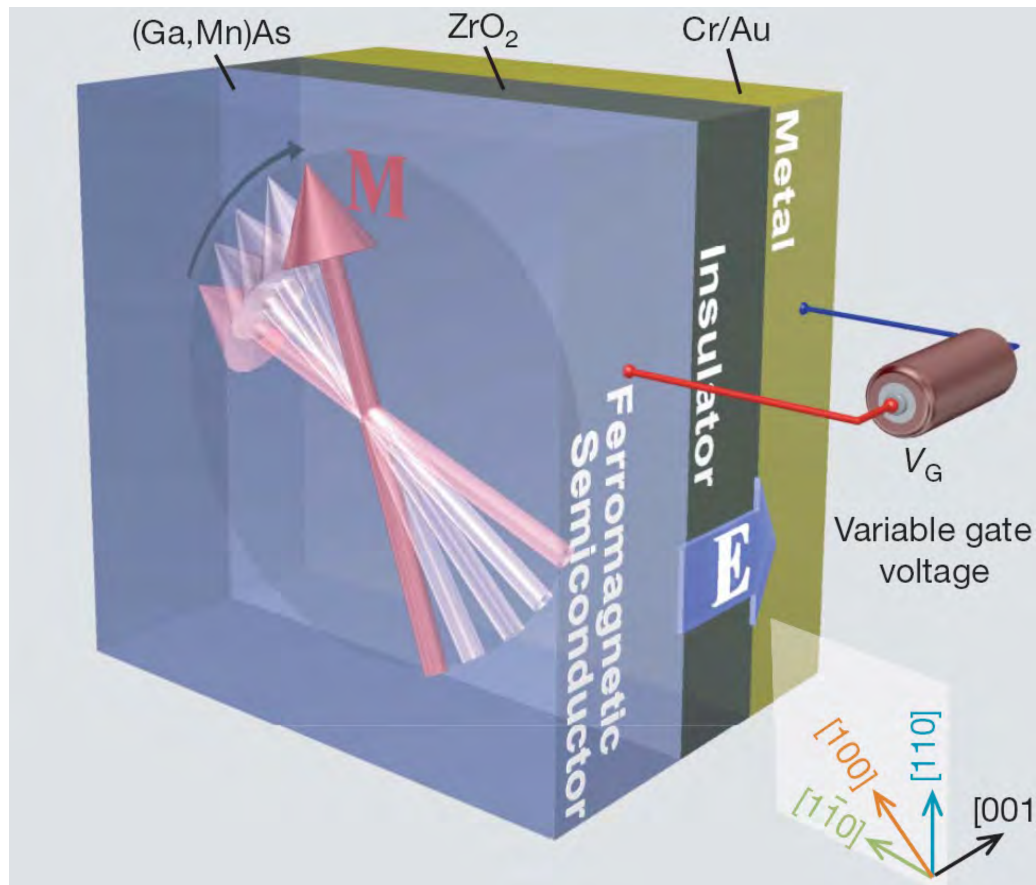


(Ga,Mn)As: ferromagnetic semiconductor

Curie temperature and magnetic moment direction controlled by electrostatic gates



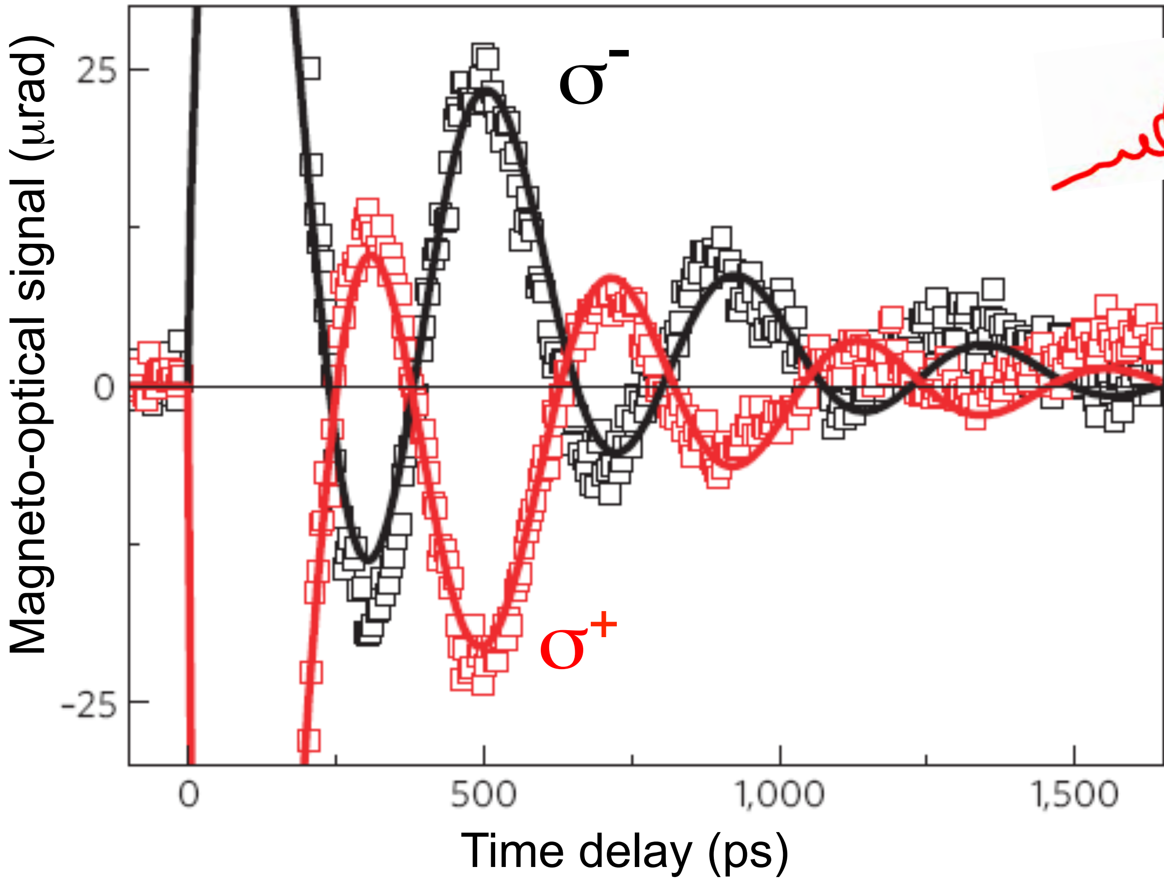
Sawicki et al. Nature Phys. 10

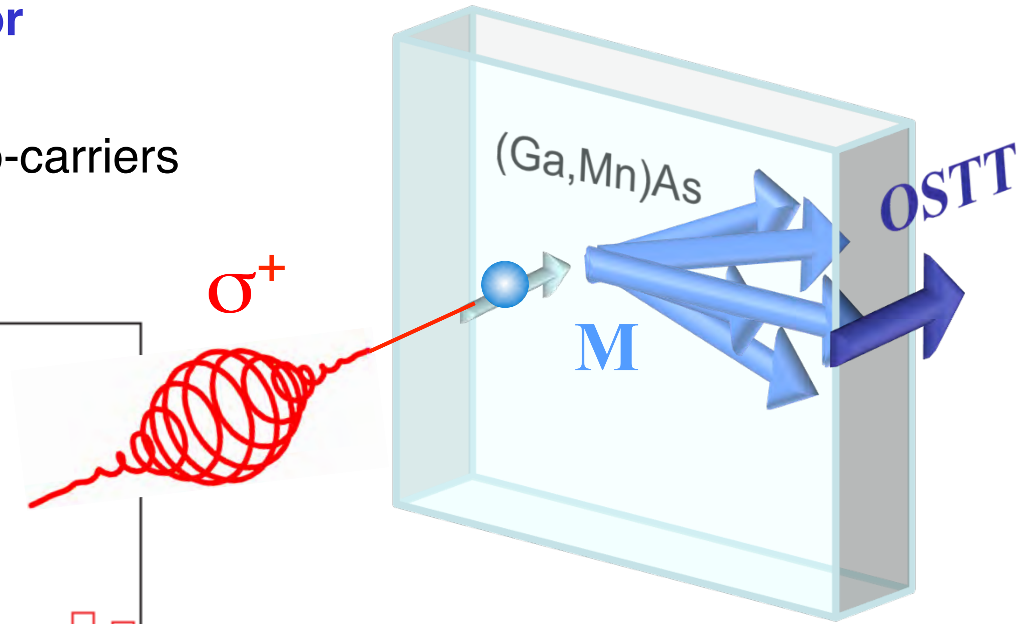


Chiba et al. Nature '08

(Ga,Mn)As: ferromagnetic semiconductor

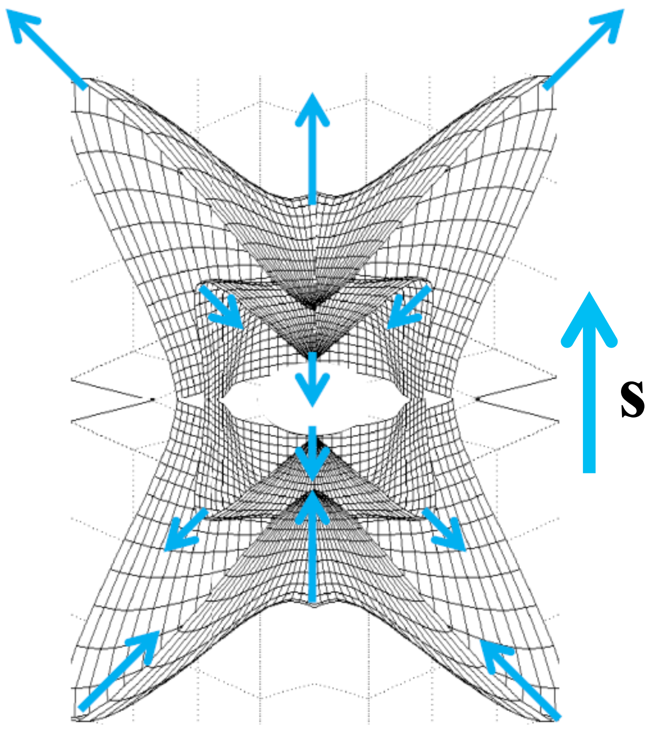
Magnetic moment direction controlled by photo-carriers



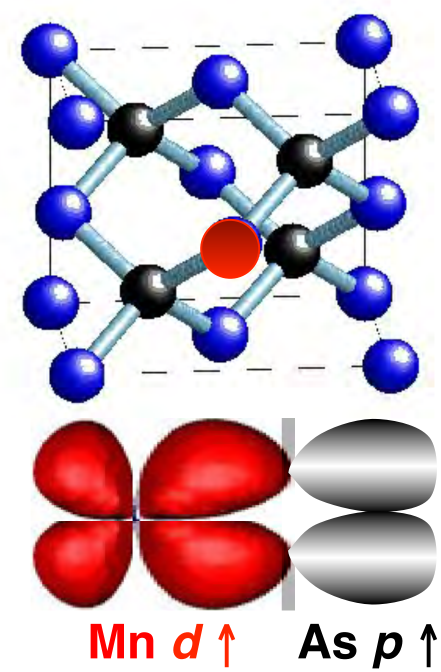


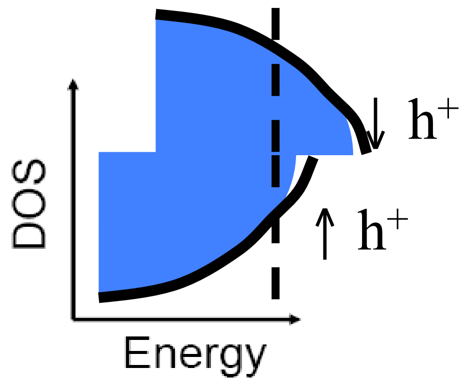
Nemec et al. Nature Phys.'12

(Ga,Mn)As: spin-orbit coupled carriers



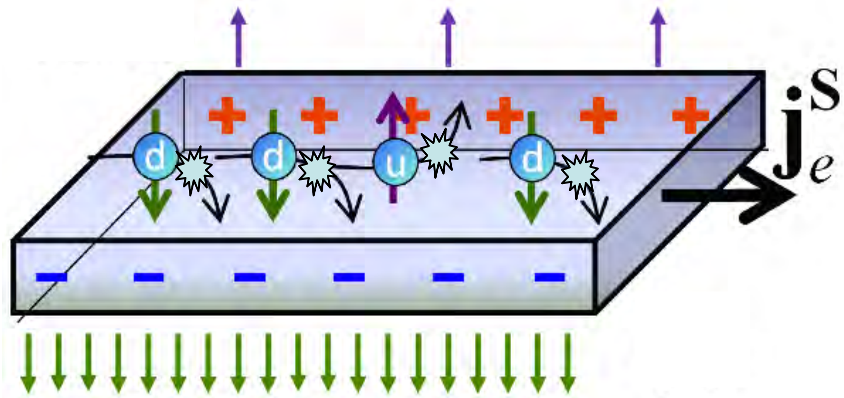
p-d hybridization



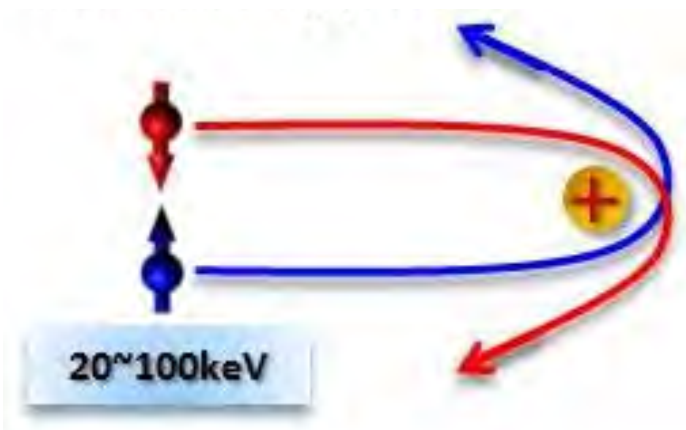


Anomalous Hall effect in FMs

Hall 1881

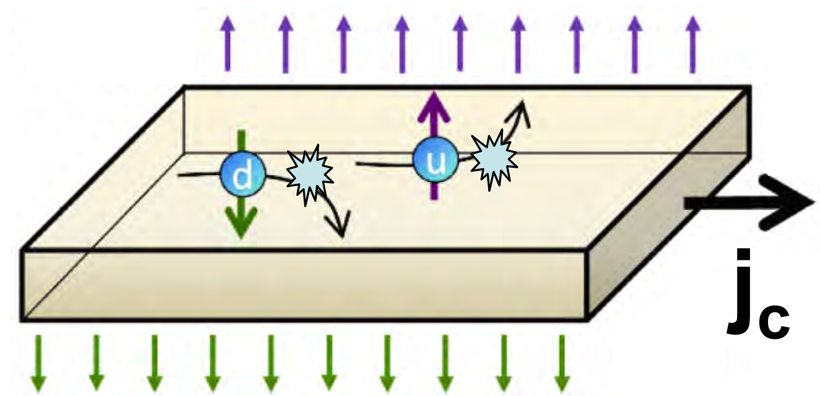


Mott scattering in (NM) vacuum



Mott, N. F. Proc. R. Soc. Lond. A 1929

Spin Hall effect in PMs

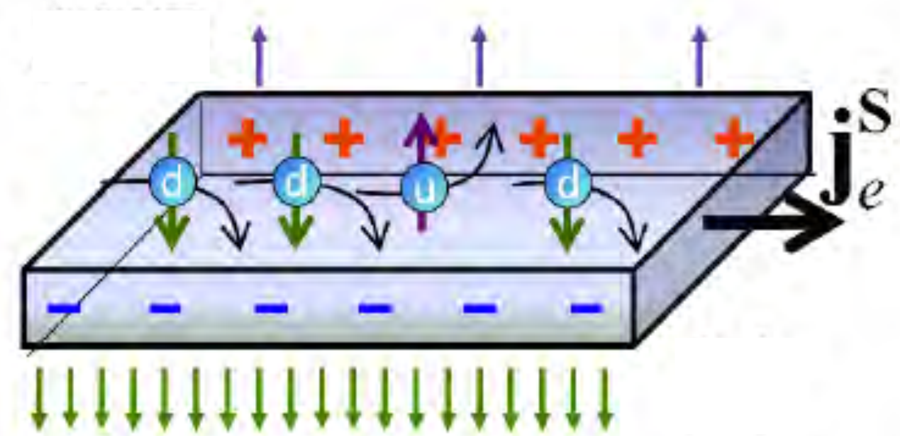


Dyakonov and Perel 1971

Kato et al., Science'04

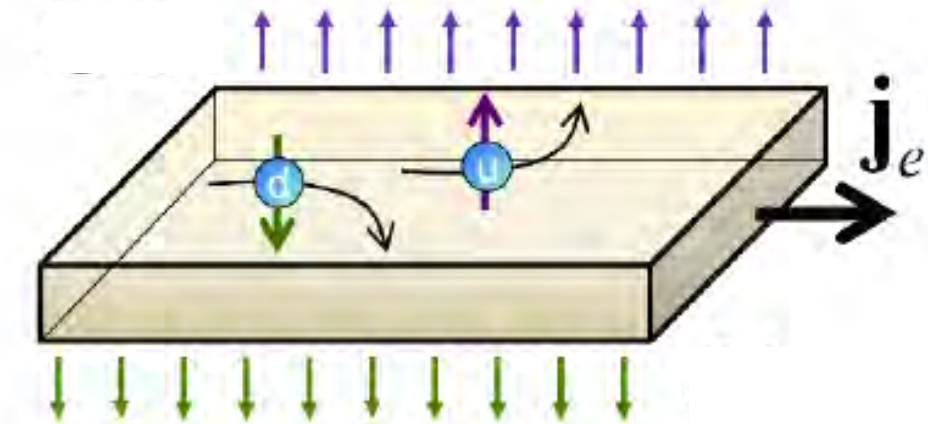
Intrinsic anoumalous Hall effect in (Ga,Mn)As

Intrinsic spin Hall effect in GaAs



FM (Ga,Mn)As

TJ et al. PRL'02



PM GaAs

Murakami, Nagaosa, & S.-C. Zhang, Science'03
Sinova et al. PRL'04

Wunderlich, TJ et al. Phys. Rev. Lett. '05

Intrinsic AHE in many FMs including Fe, Co, Ni,...

Nagaosa et al. RMP'10

Intrinsic SHE in many PMs including Pt, Pd, Ta,...

Tanaka et al. PRB '08, TJ et al. Nature Mater. '12, Sinova et al. RMP '15

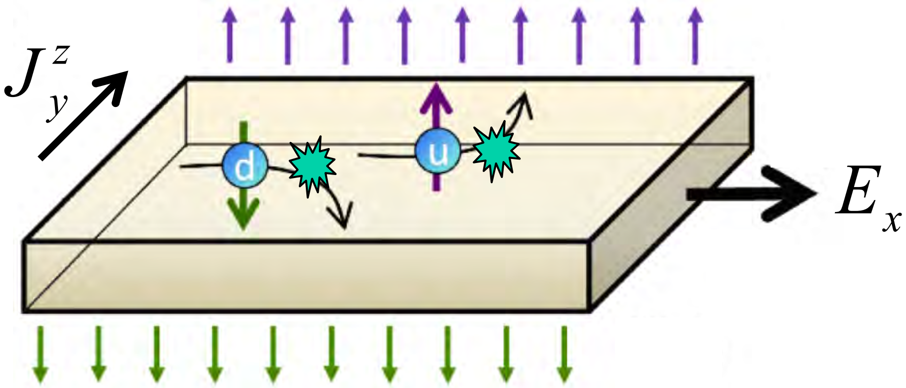
relativistic & scattering-independent

Linear response I. (condensed matter class)

Boltzmann theory : non-equilibrium distribution function and equilibrium states

Extrinsic (skew-scattering) SHE/AHE

$$J_y^z = \frac{e}{V}\sum_{k,n} j^{z,y}_{0n,\vec{k}}\, g_{n,\vec{k}}(E_j)$$



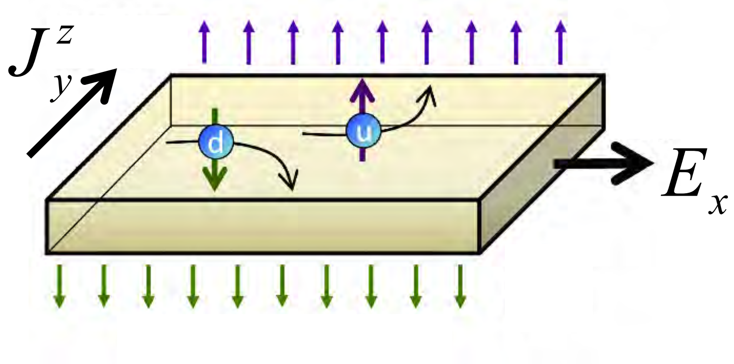
$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(\varepsilon_{n,\vec{k}})$$

$$e\vec{E}\cdot\vec{v}_{0n,\vec{k}}\,\frac{\partial f_0(\varepsilon_{n,\vec{k}})}{\partial \varepsilon_{n,\vec{k}}} = -\frac{1}{V}\sum_{k,n} W_{n,\vec{k},n',\vec{k}'}\,(f_{n,\vec{k}} - f_{n',\vec{k}'})$$

Linear response II. (quantum mechanics class)

Perturbation theory: equilibrium distribution function and non-equilibrium states

Intrinsic SHE/AHE

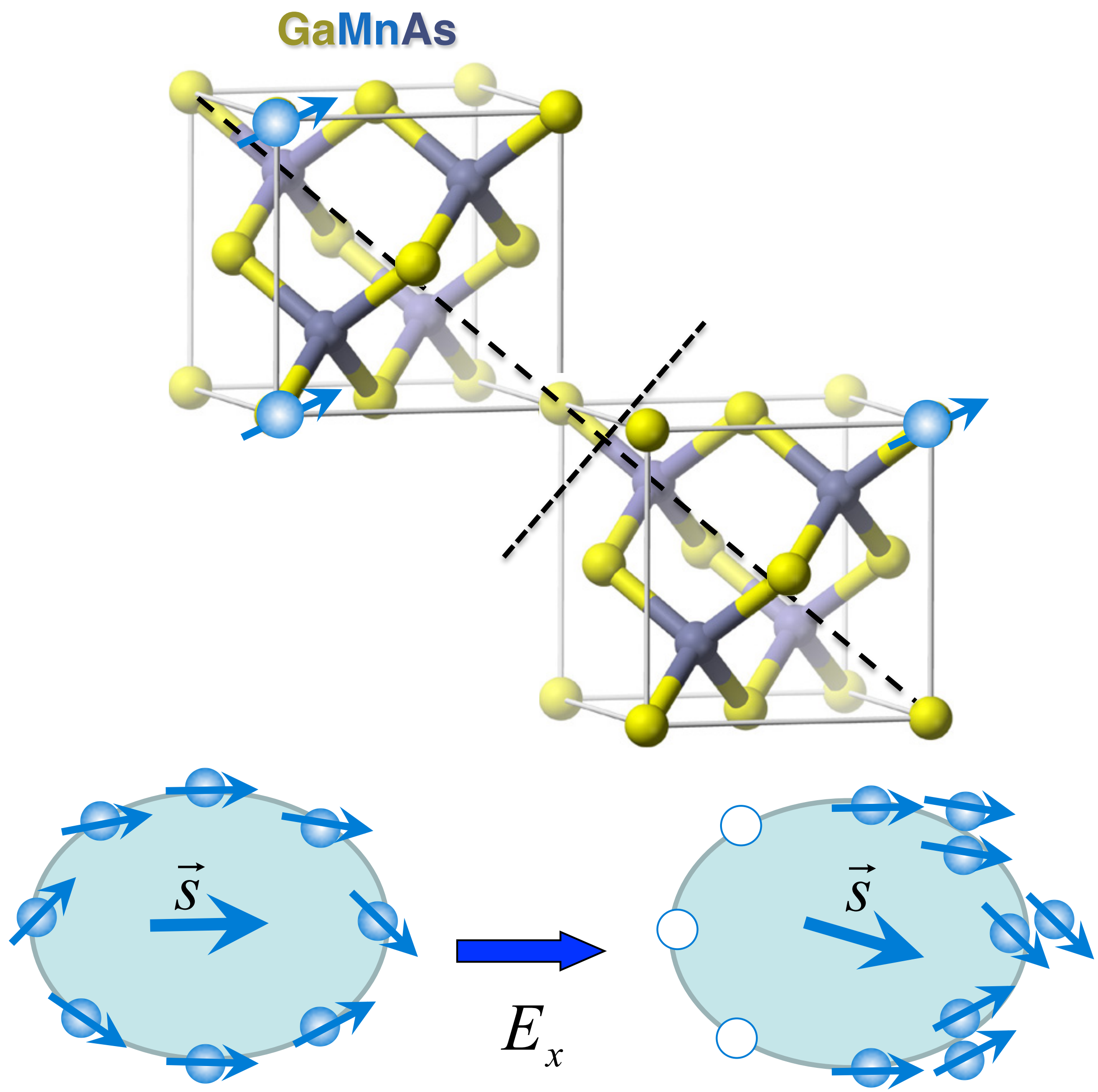


$$J_y^z = \sum_l \langle \psi_l(t) | \hat{j}_y^z | \psi_l(t) \rangle f_0(\varepsilon_l)$$

$$|\psi_l(t)\rangle = |l\rangle e^{-i\varepsilon_l t/\hbar} + \frac{e}{i\omega} \sum_{l' \neq l} |l'\rangle \frac{\langle l' | \vec{E}\cdot\hat{v} | l \rangle e^{-i\omega t}}{\varepsilon_l - \varepsilon_{l'} + \hbar\omega} e^{-i\varepsilon_{l'} t/\hbar} + \cdots$$

$$J_y^z = \frac{e\hbar}{V} \sum_{\vec{k}, n \neq n'} (f^0_{\vec{k},n'} - f^0_{\vec{k},n}) \frac{\mathrm{Im}[\langle k, n' | \hat{j}_y^z | \vec{k}, n \rangle \langle \vec{k}, n | \vec{v}\cdot\vec{E} | \vec{k}, n' \rangle]}{(\varepsilon_{\vec{k},n'} - \varepsilon_{\vec{k},n})^2}$$

(Ga,Mn)As: spin-orbit coupled and inversion asymmetric carrier bands



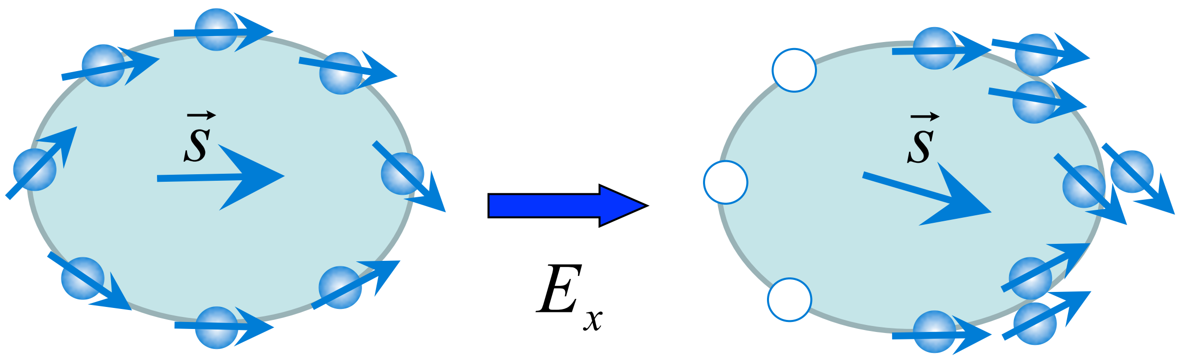
Bernevig & Vafek, PRB '05, Chernyshev et al. Nature Phys.'09, Fang et al. Nature Nanotech.'11

Linear response I. (condensed matter class)

Boltzmann theory : non-equilibrium distribution function and equilibrium states

Extrinsic inverse spin galvanic effect (ISGE)

$$\vec{S} = \frac{1}{V}\sum_{k,n} \vec{s}_{0n,\vec{k}}\, g_{n,\vec{k}}(E_j)$$



$$g_{n,\vec{k}} = f_{n,\vec{k}} - f_0(\varepsilon_{n,\vec{k}})$$

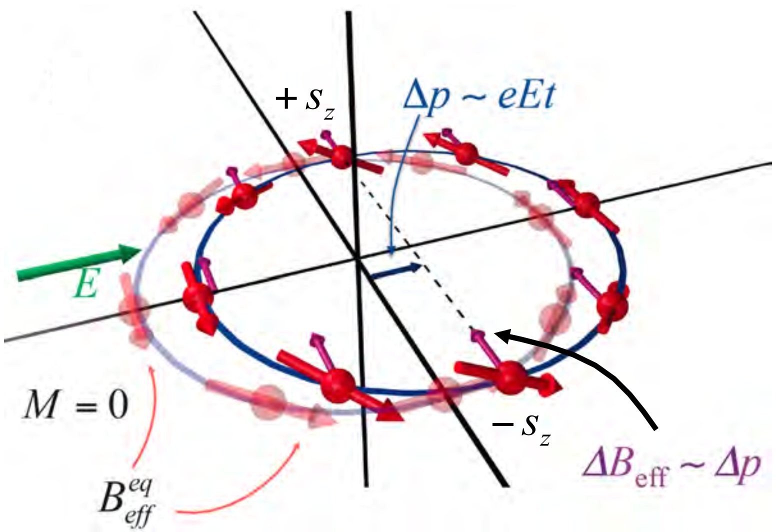
$$e\vec{E}\cdot\vec{v}_{0n,\vec{k}}\frac{\partial f_0(\varepsilon_{n,\vec{k}})}{\partial \varepsilon_{n,\vec{k}}} = -\frac{1}{V}\sum_{k,n} W_{n,\vec{k},n',\vec{k}'}(f_{n,\vec{k}} - f_{n',\vec{k}'})$$

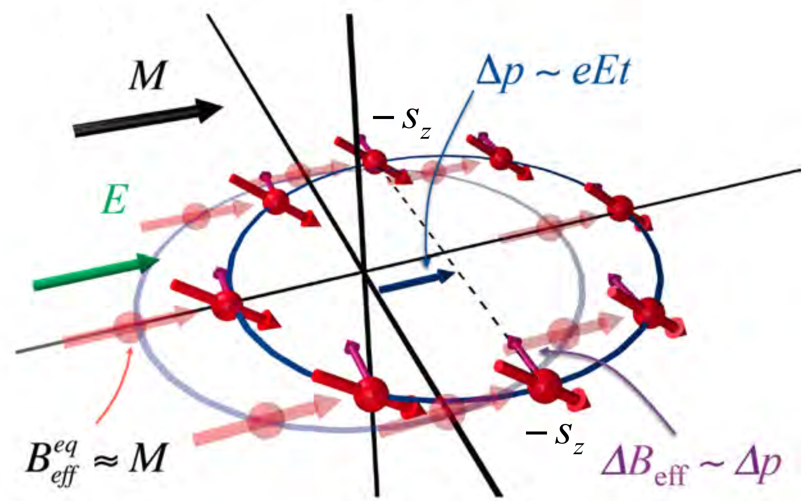
Linear response II. (quantum mechanics class)

Perturbation theory: equilibrium distribution function and non-equilibrium states

Intrinsic SHE

$$J_y^z = \frac{e\hbar}{V}\sum_{\vec{k},n\neq n'}(f^0_{\vec{k},n'} - f^0_{\vec{k},n})\frac{\mathrm{Im}[\langle k,n'|\hat{j}_y^z|\vec{k},n\rangle\langle\vec{k},n|\vec{v}\cdot\vec{E}|\vec{k},n'\rangle]}{(\varepsilon_{\vec{k},n'}-\varepsilon_{\vec{k},n})^2}$$



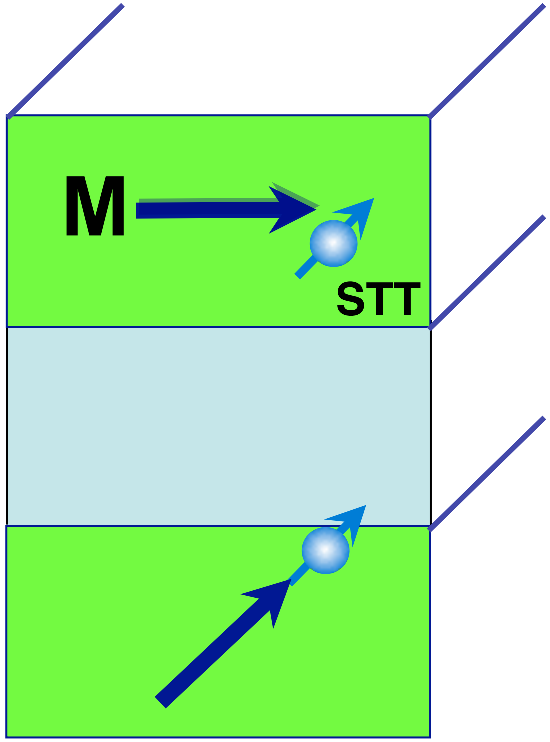


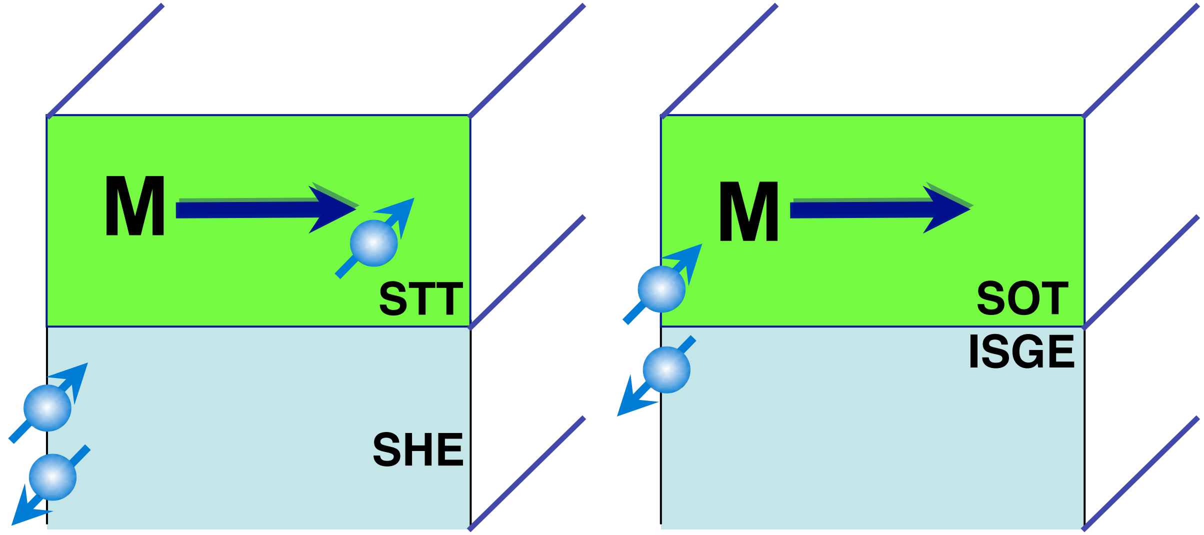
Intrinsic ISGE

$$S^z = \frac{e\hbar}{V}\sum_{\vec{k},n\neq n'}(f^0_{\vec{k},n'} - f^0_{\vec{k},n})\frac{\mathrm{Im}[\langle k,n'|\hat{s}^z|\vec{k},n\rangle\langle\vec{k},n|\vec{v}\cdot\vec{E}|\vec{k},n'\rangle]}{(\varepsilon_{\vec{k},n'}-\varepsilon_{\vec{k},n})^2}$$

Kurebayashi et al., Nature Nanotech. '14

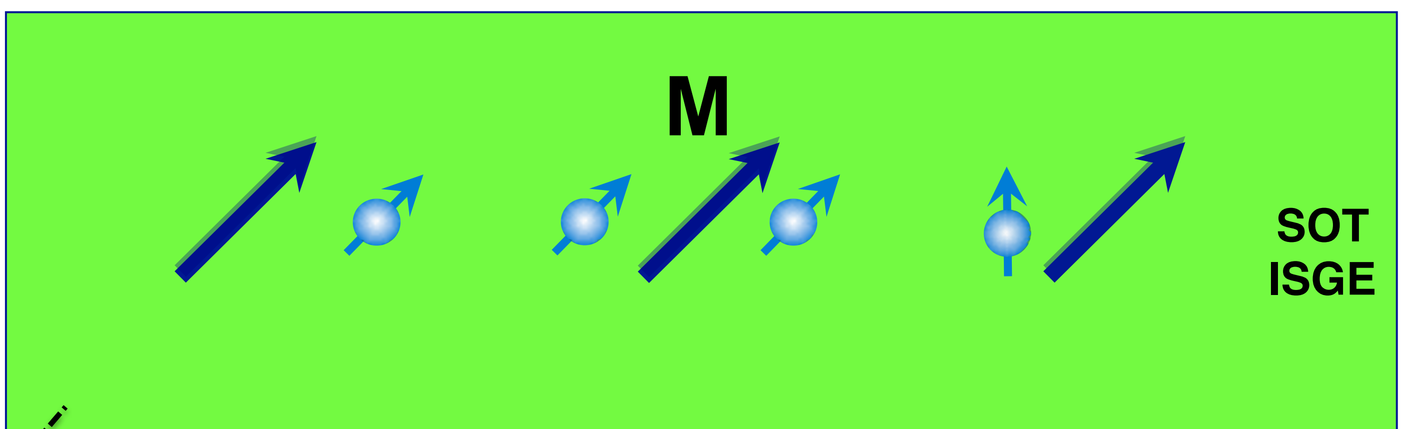
Spin torques

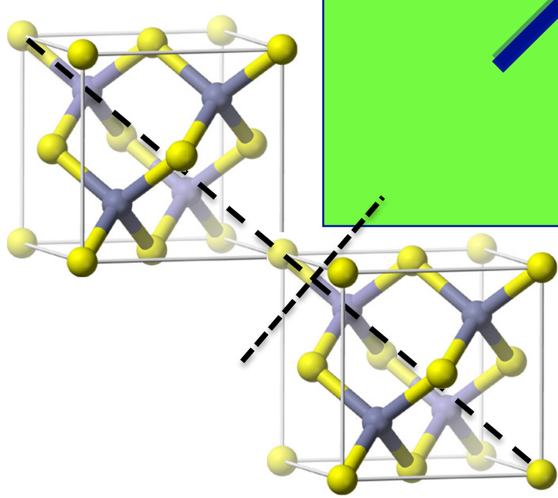




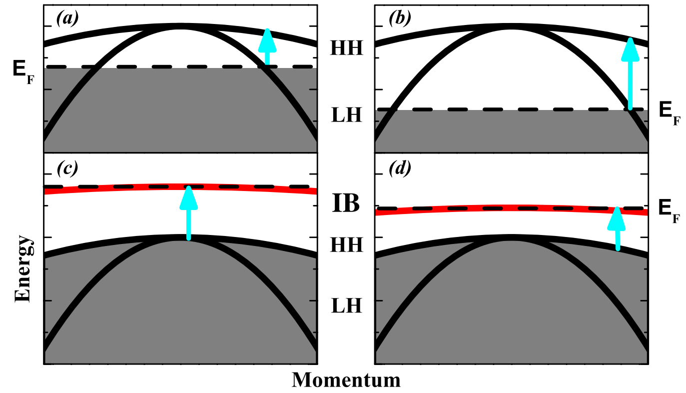
Miron et al. Nature '11, Liu et al. Science '12

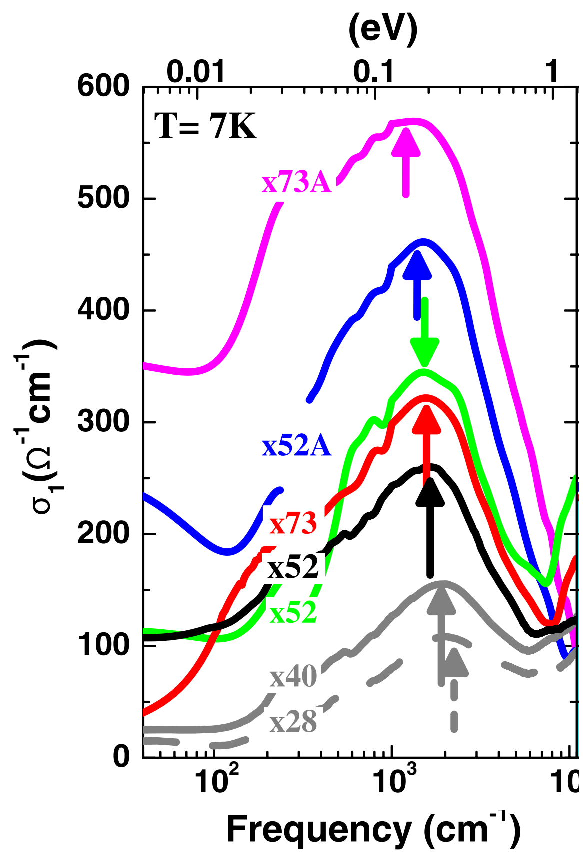
Slonczewski, Berger, 1996





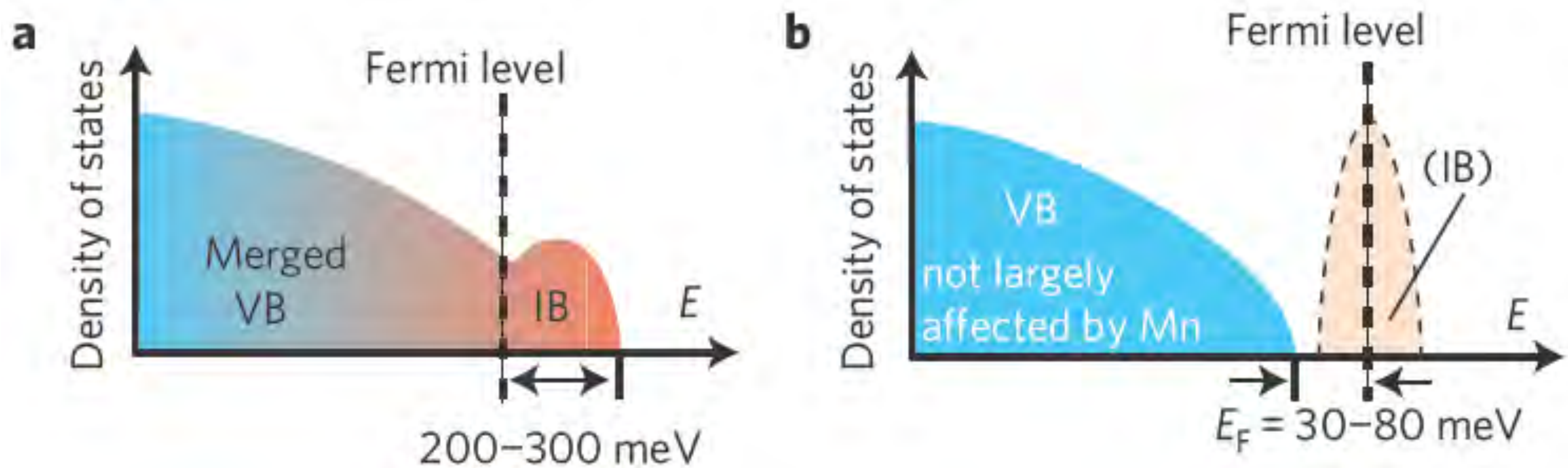
Infrared absorption





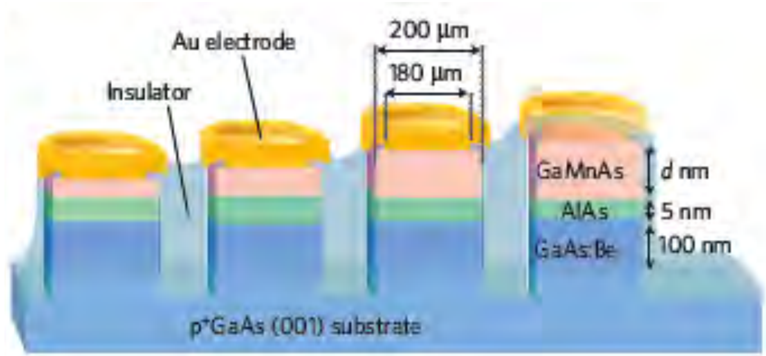
Burch et al. PRL ’06

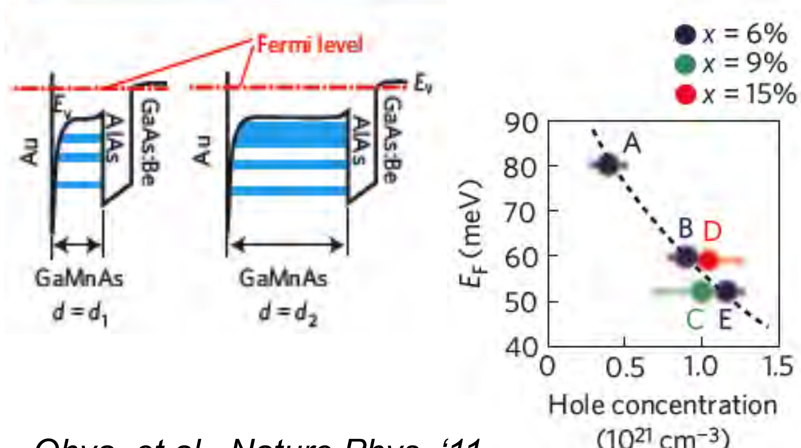
Resonant tunneling spectroscopy



EF ~100‘s meV in merged VB-IB

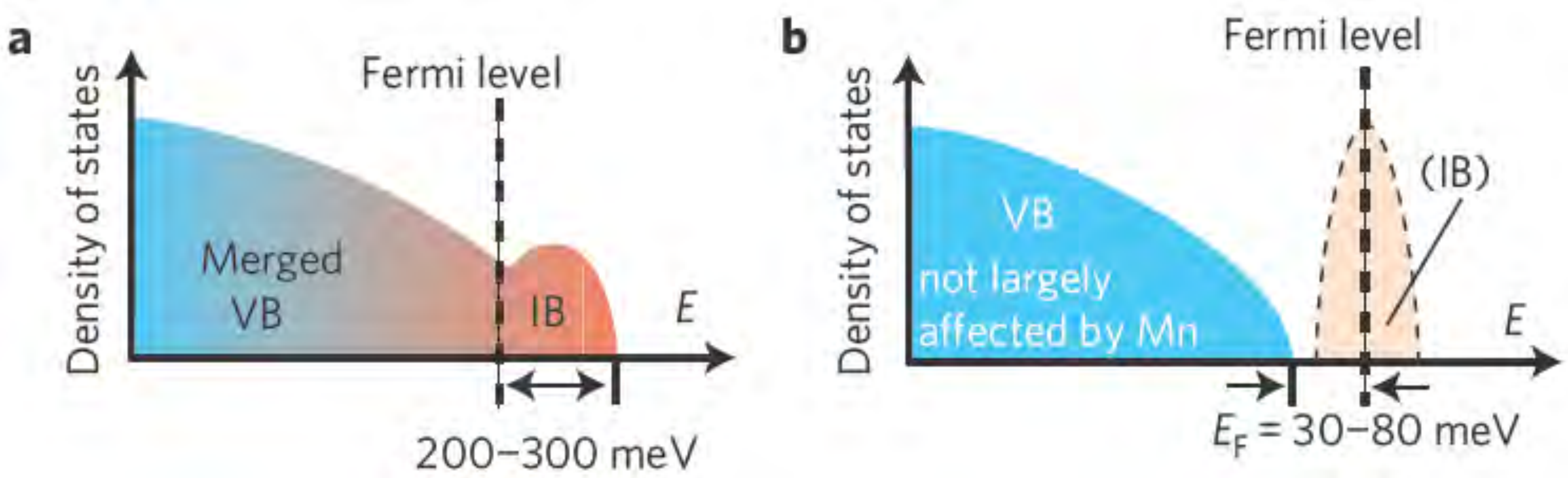
EF ~10‘s meV above VB in detached IB





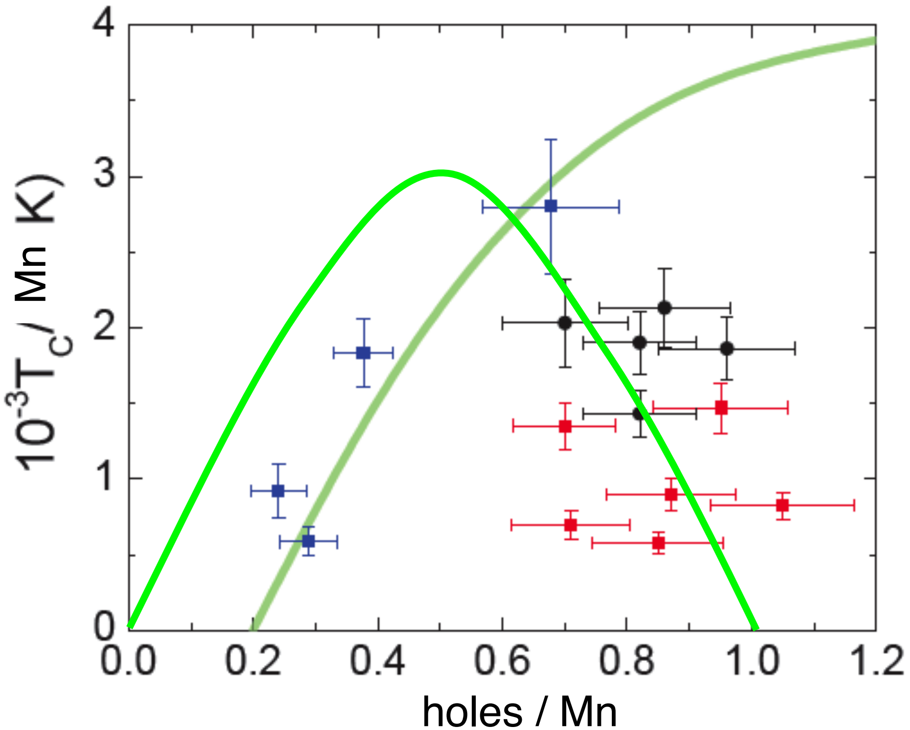
Ohya et al., Nature Phys. ‘11

Curie temperature



p-d kinetic-exchange:

T_c inreases with # of holes in merged VB-IB

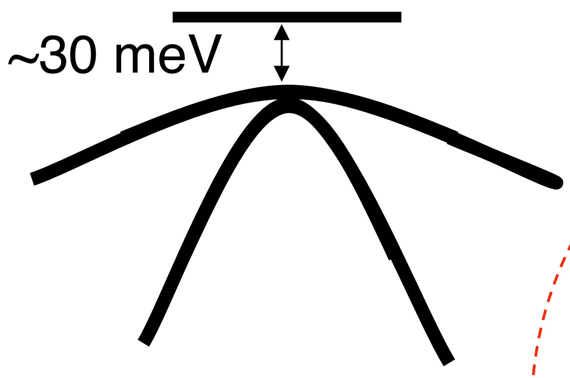


d-d double-exchange:

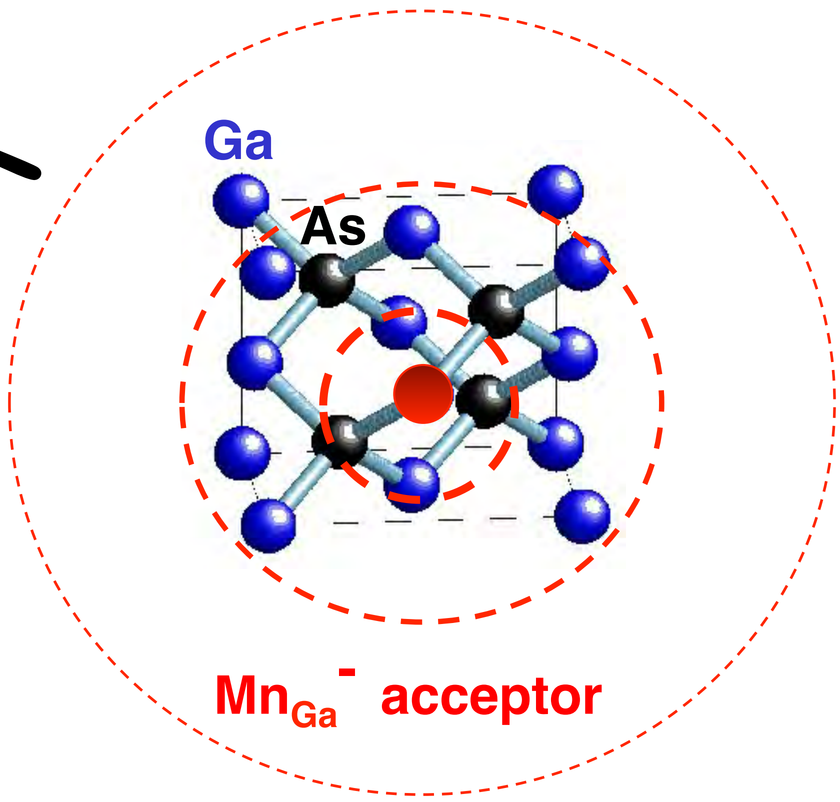
max T_c at half filling of detached IB

Dobrowolska et al. Nature Mat. '12

Microscopics of the conventional semiconductor valence-band picture



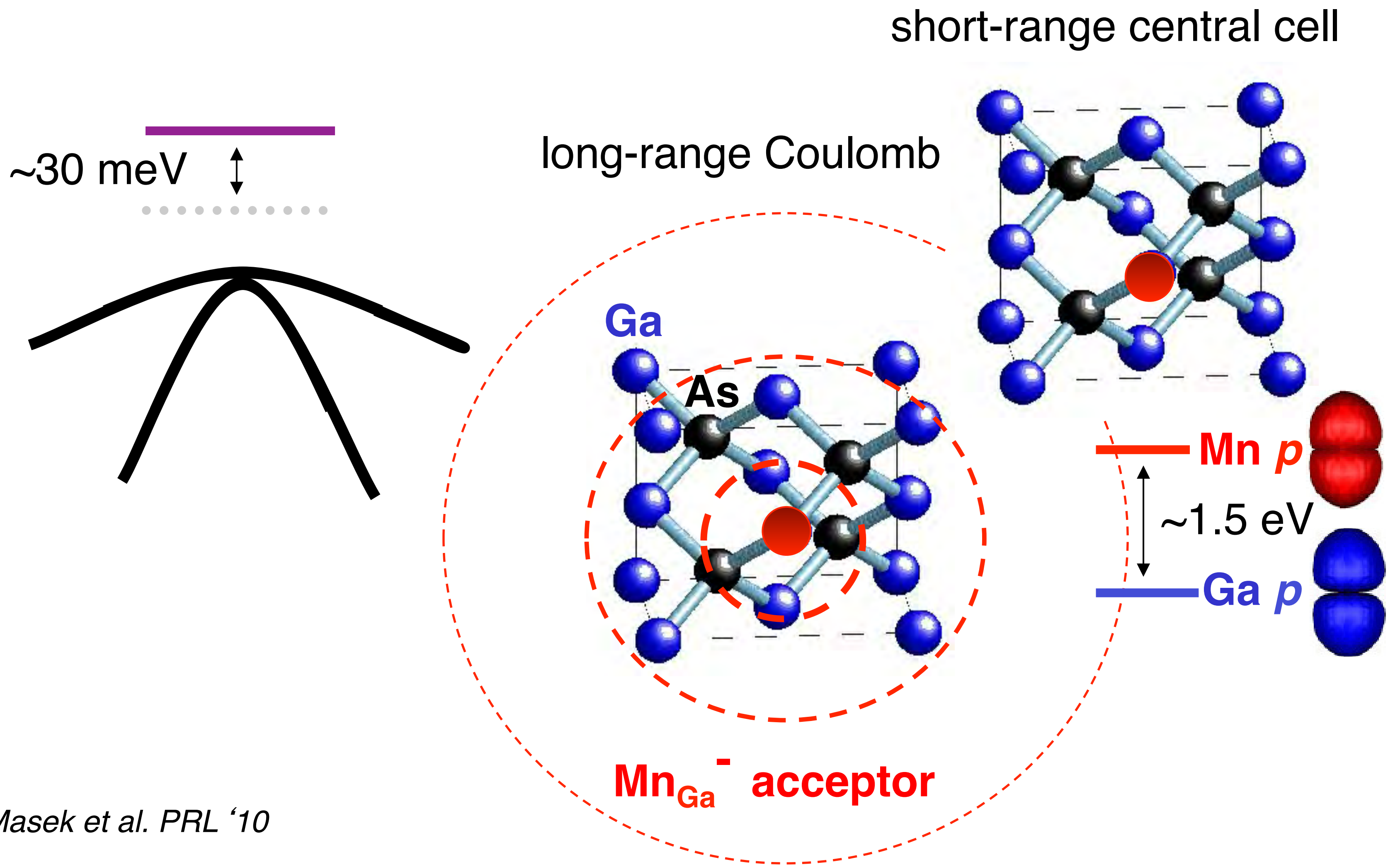
long-range Coulomb



Mn_{Ga}^{-} acceptor

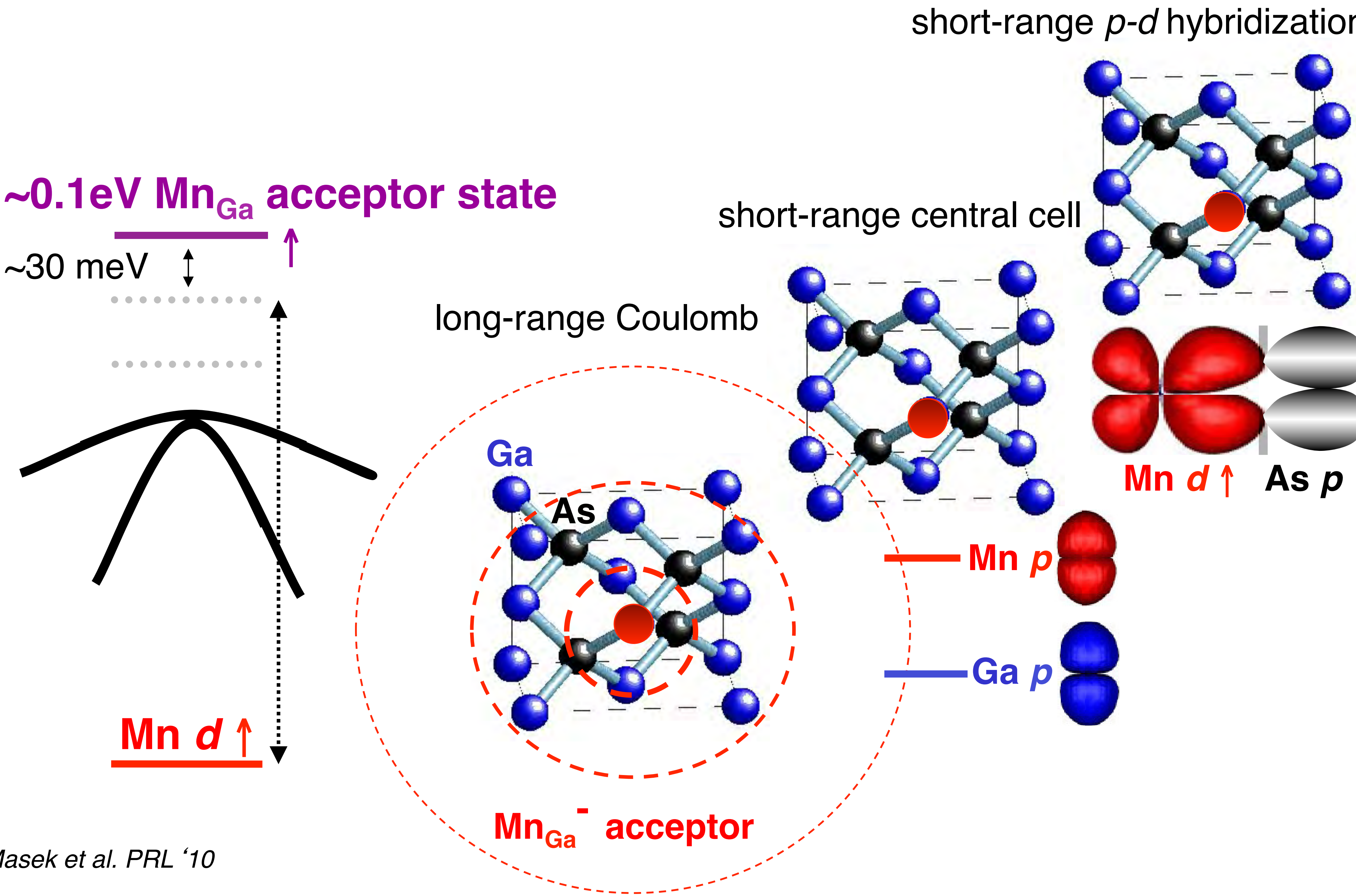
Masek et al. PRL '10

Microscopics of the conventional semiconductor valence-band picture



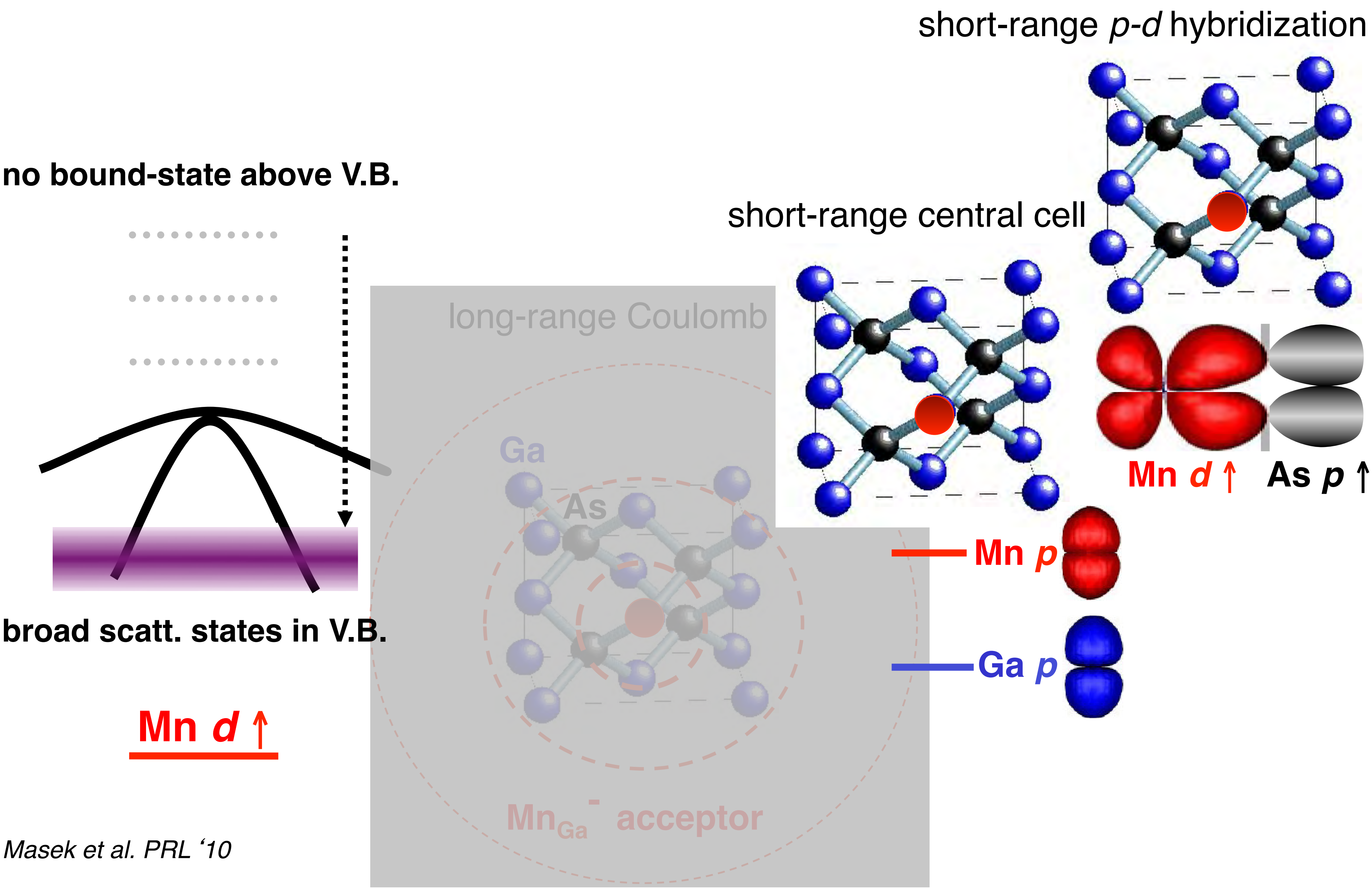
Masek et al. PRL ‘10

Microscopics of the conventional semiconductor valence-band picture



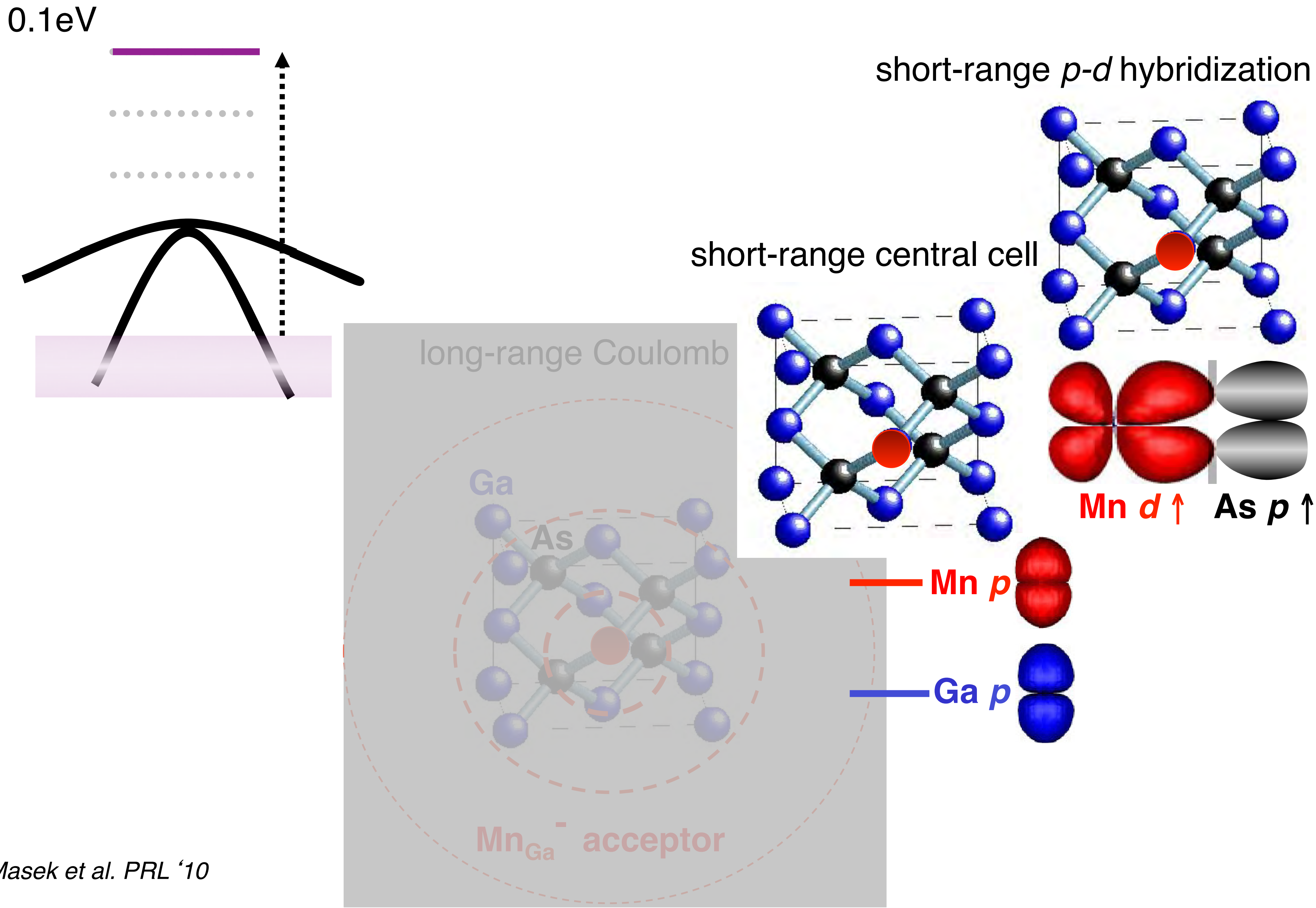
Masek et al. PRL '10

Microscopics of the conventional semiconductor valence-band picture

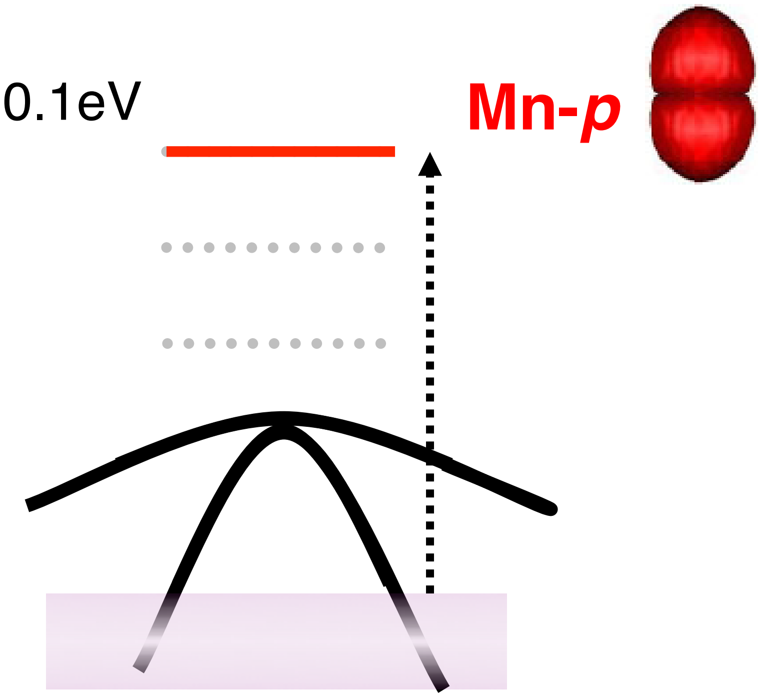


Masek et al. PRL '10

Impurity-band picture: binding primarily due to short-range potentials (screening and IB broadening play minor role)



Masek et al. PRL '10

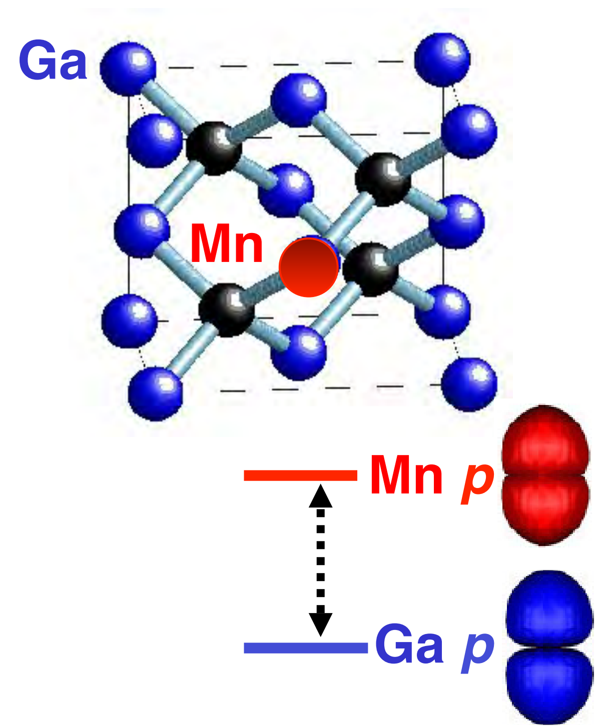


Microscopic realization of IB picture #1

cannot use DFT (too much *ab initio*)

→ TBA ideal tool

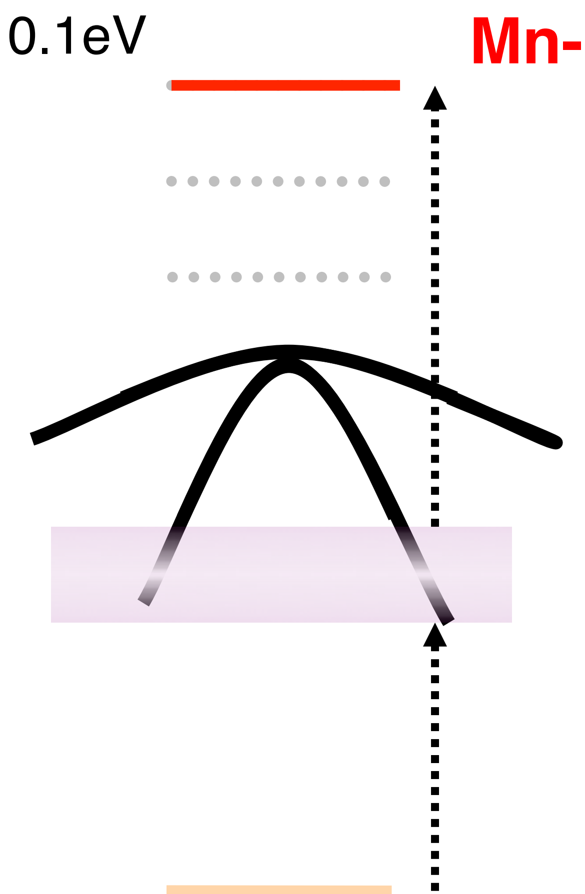
short-range central cell



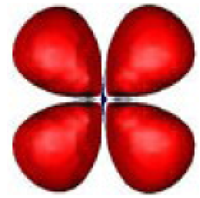
TBA^p : no bound-state even for Mn *p*-level shifts > 10's eV

Masek et al. PRL '10

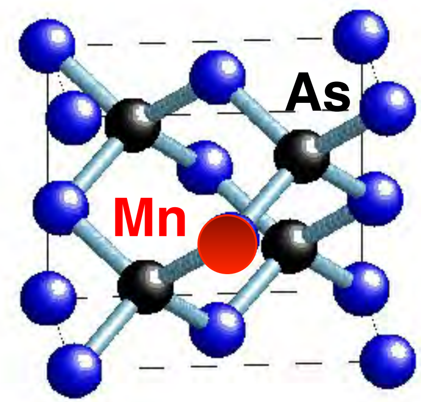
Microscopic realization of IB picture #2

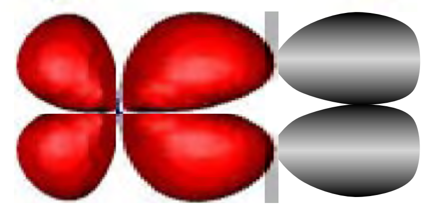


Mn-*d*



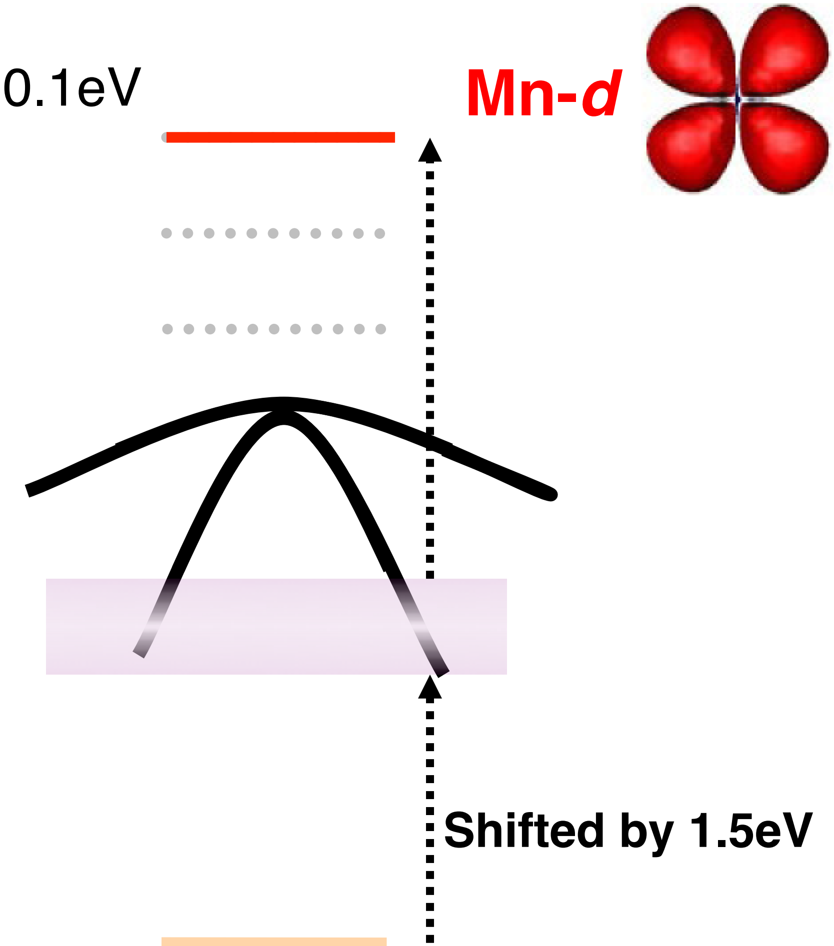
short-range *p-d* hybridization

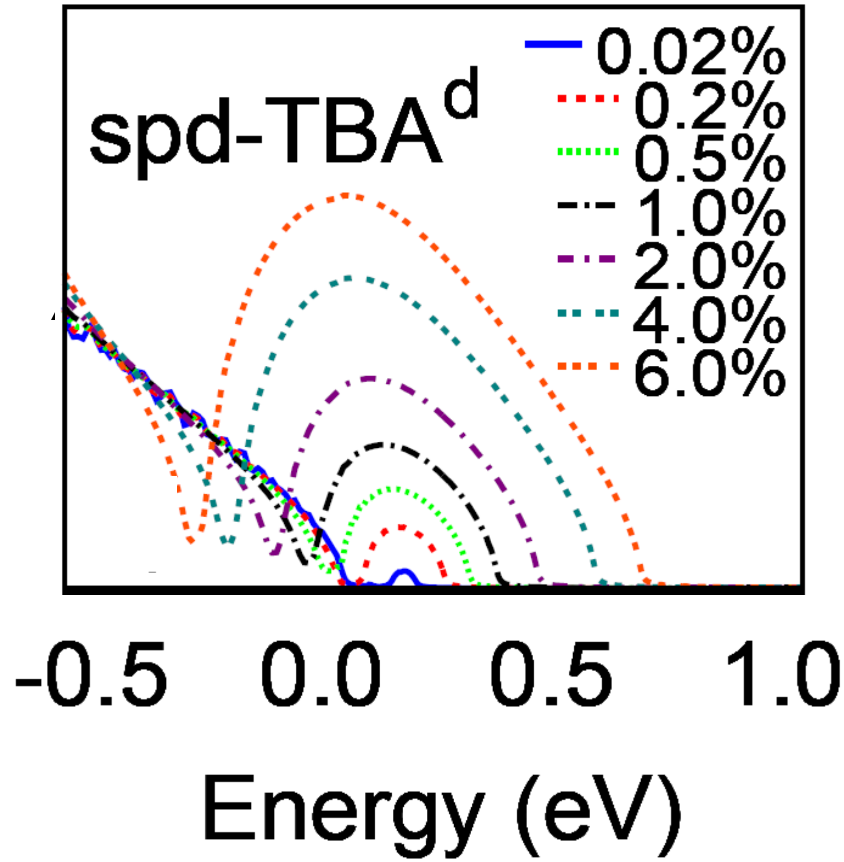




$$\sim \frac{|\langle d \,|\, V \,|\, p \rangle|^2}{|\, E_d \,|}$$

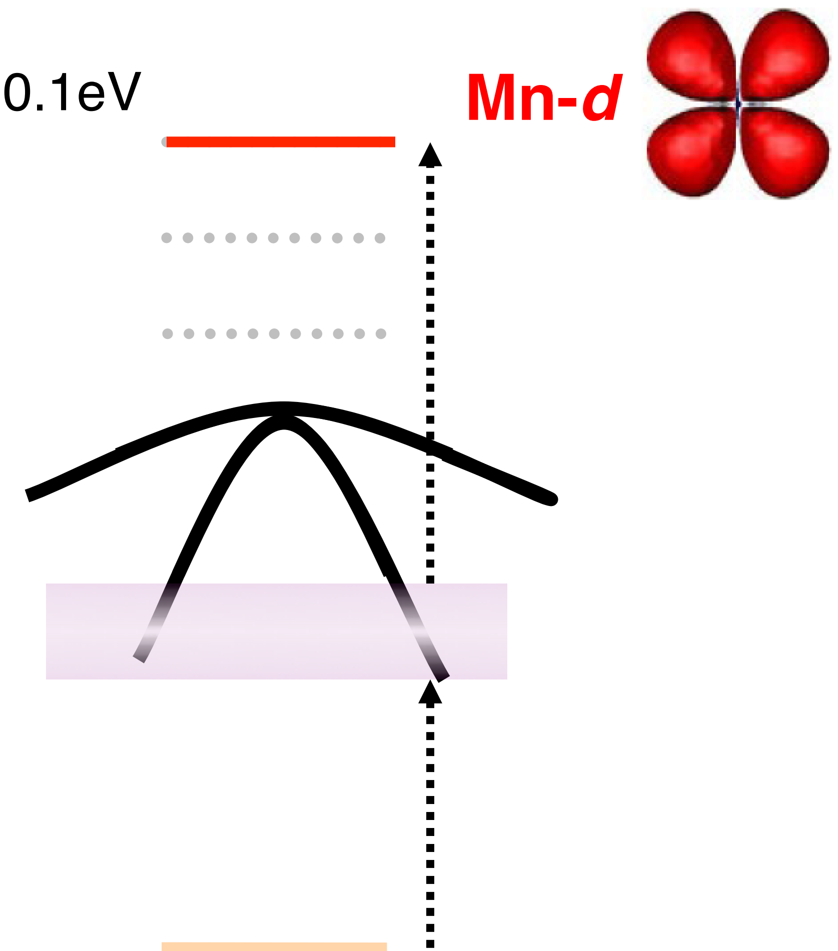
Masek et al. PRL ‘10

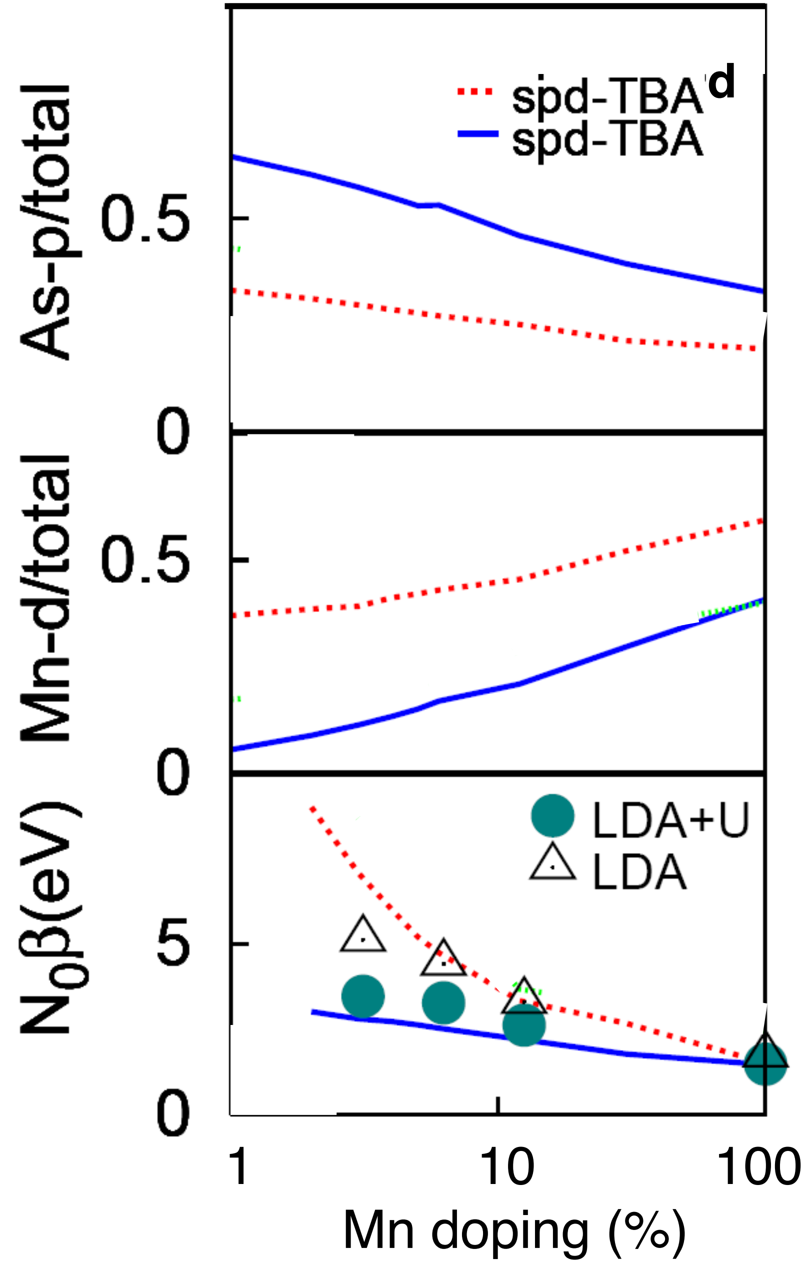




TBA^{d} : no detached narrow (<0.1eV) IB at >0.2% Mn

Masek et al. PRL '10



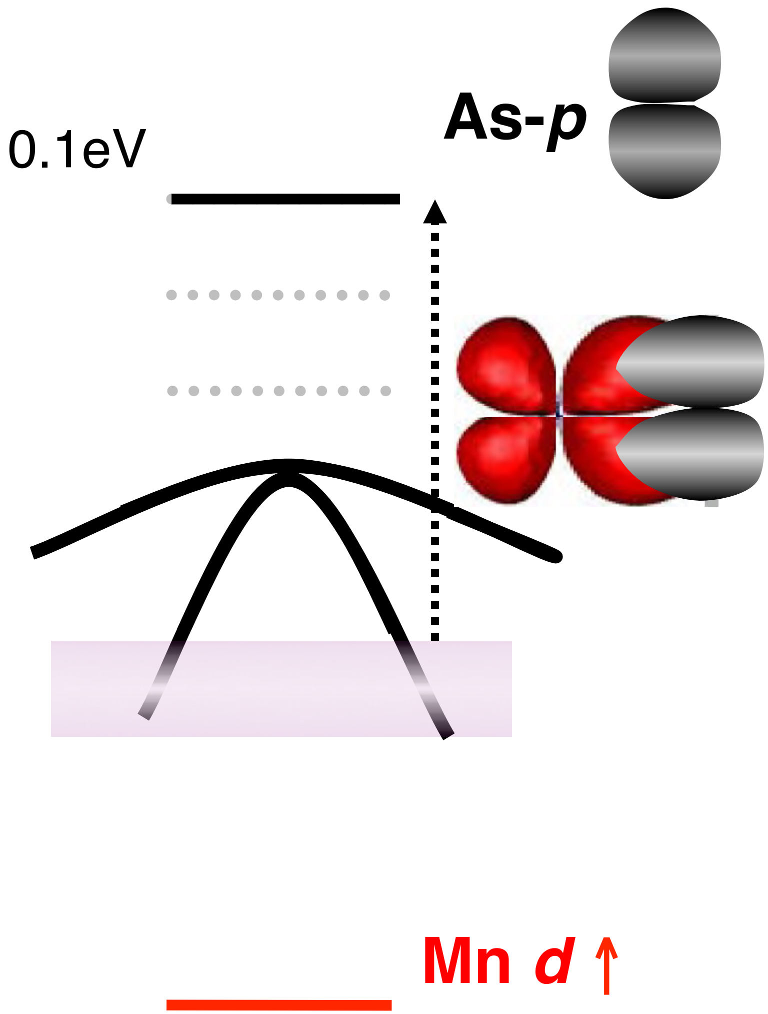


TBA^d : not dominant Mn d but still mixed with As(Ga) p

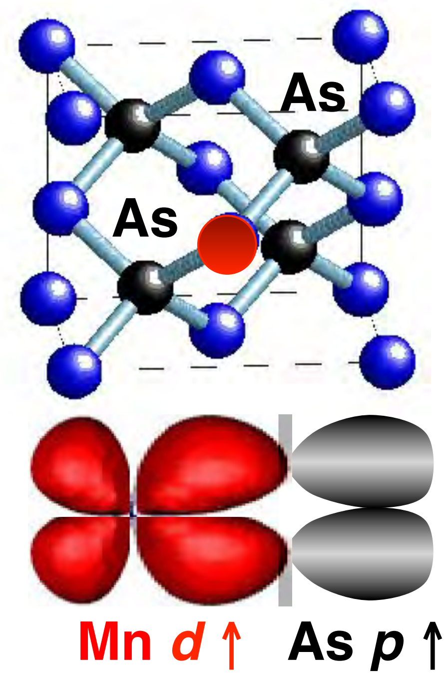
Exchange splitting $N_0\beta$ > then experimental limits (1-3 eV)

Masek et al. PRL '10

Microscopic realization of IB picture #3

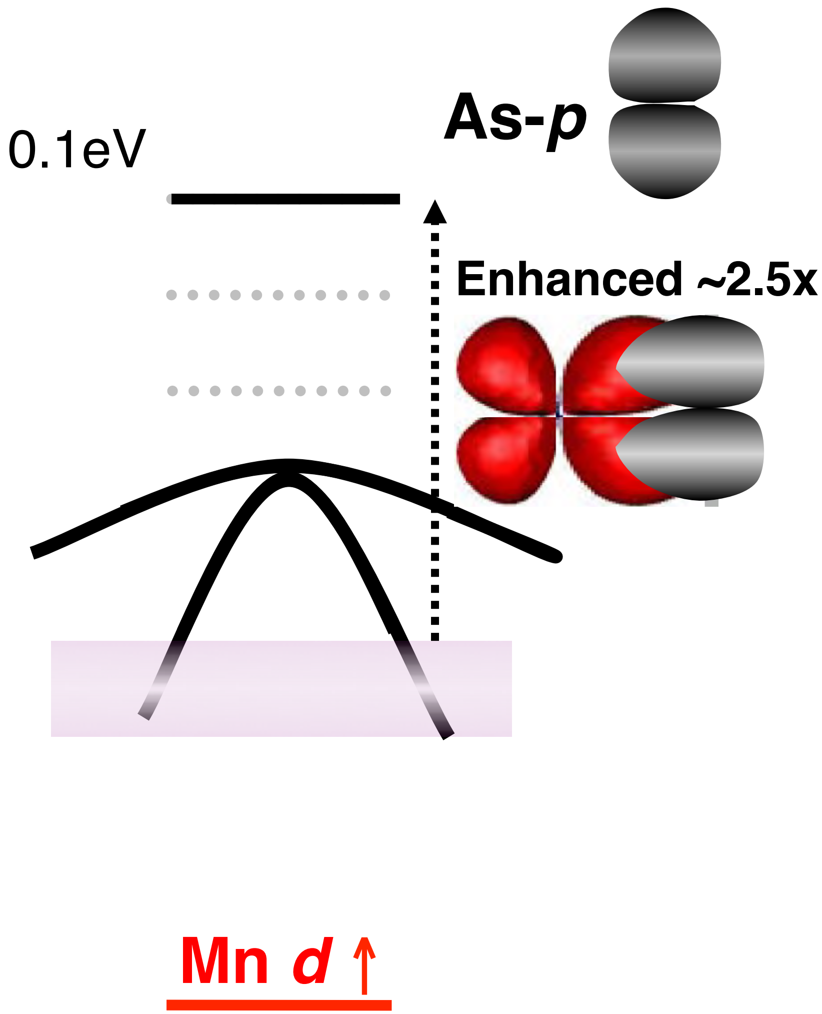


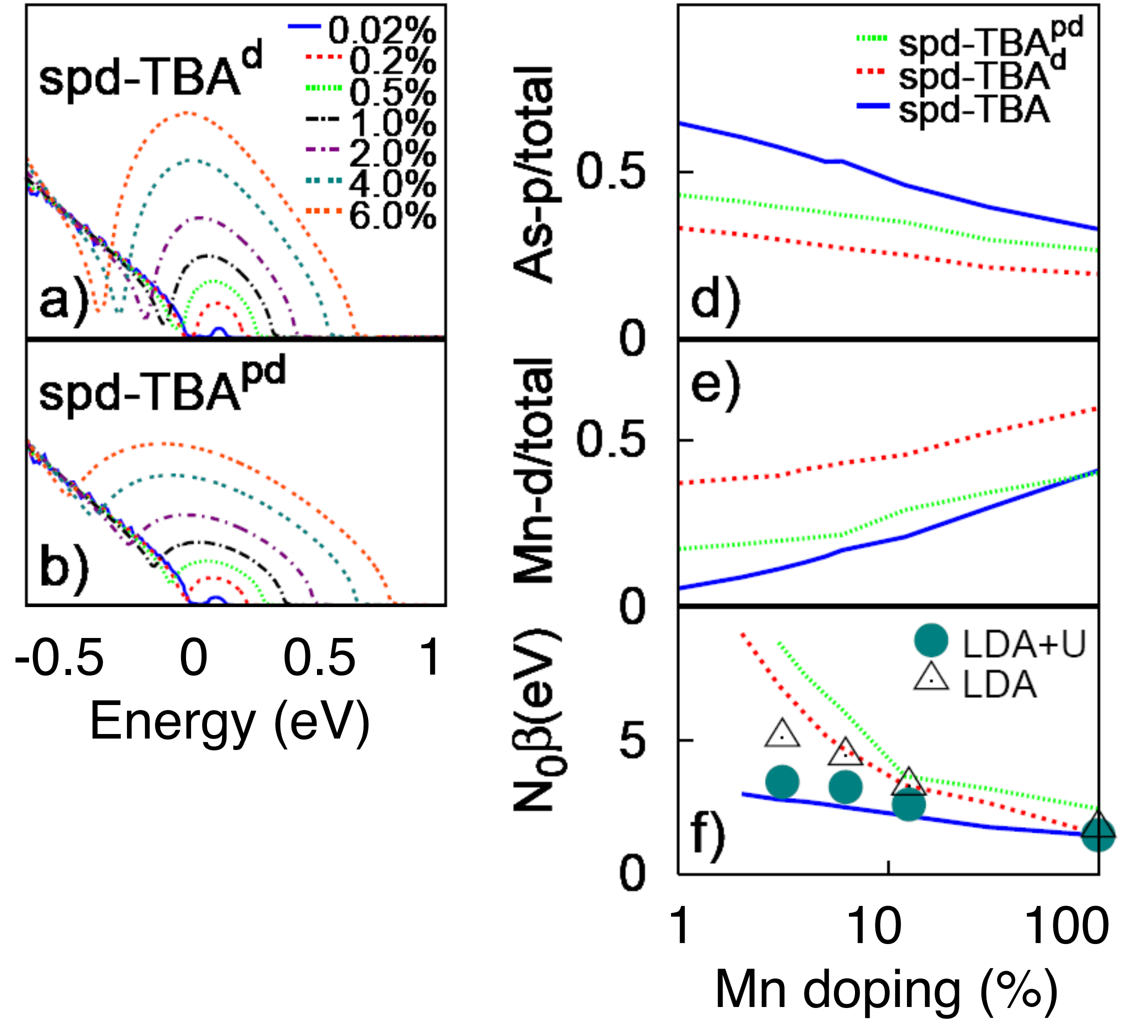
short-range *p-d* hybridization



$$\sim \frac{|\langle p \,|\, V \,|\, d \rangle|^2}{|\, E_d \,|}$$

Masek et al. PRL ‘10





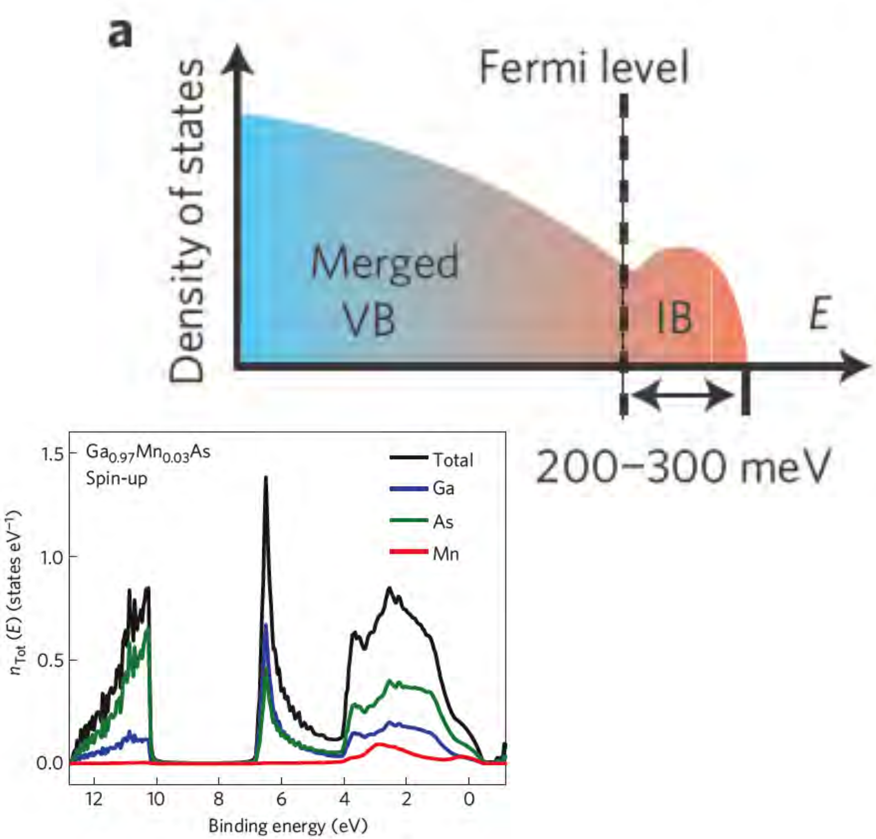
TBA^{pd}: still dominated by As(Ga)p

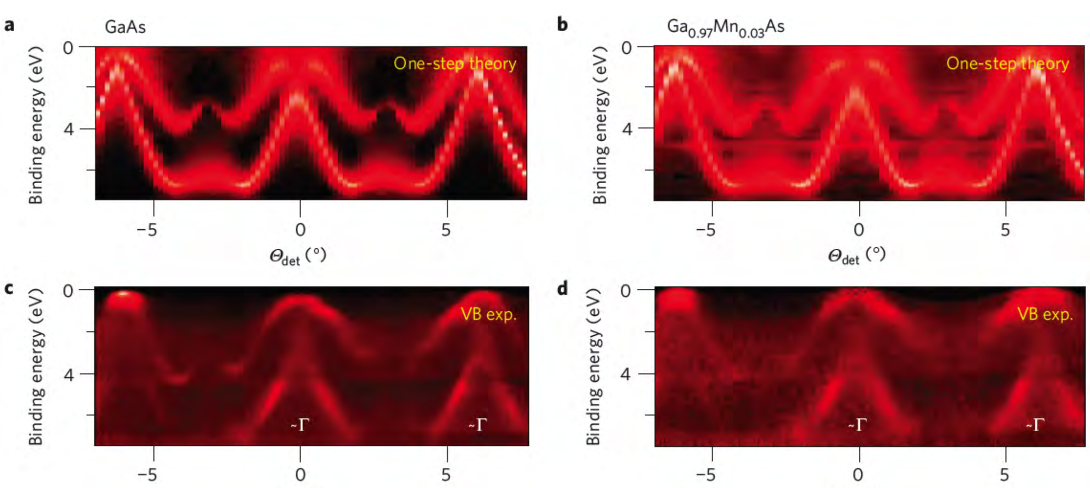
no detached narrow (<0.1eV) IB at >0.2% Mn

Exchange splitting $N_0\beta$ > then experimental limits (1-3 eV)

Masek et al. PRL '10

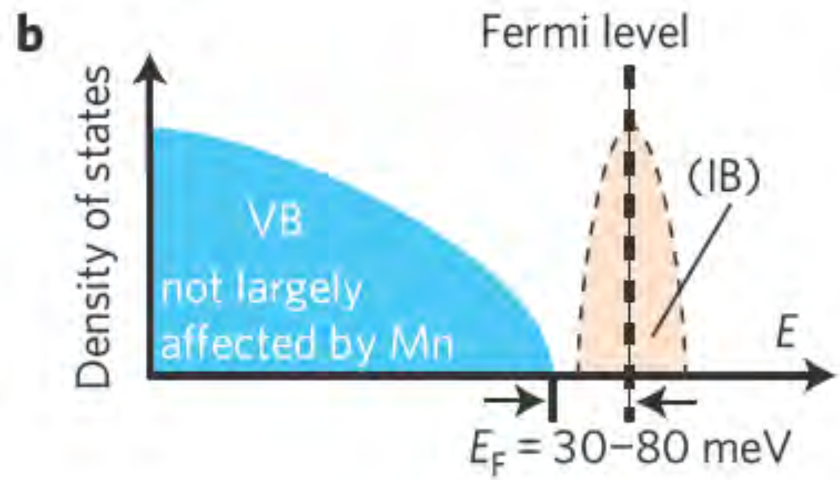
Angle-resolved photoemission

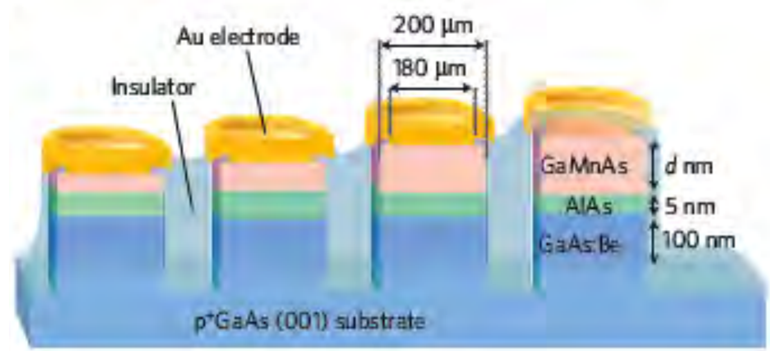


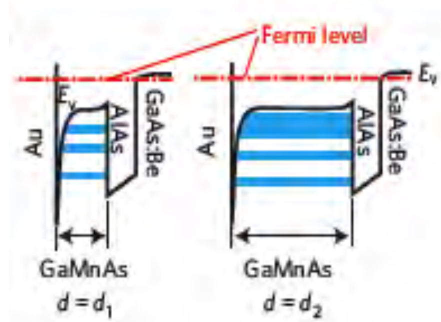


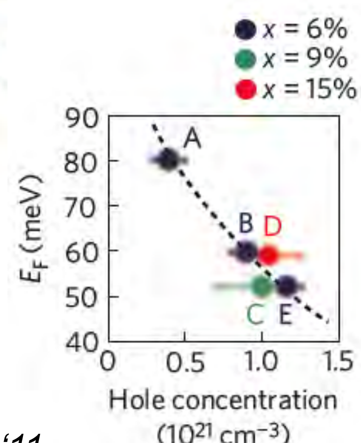
Gray et al., Nature Mat. '12

Resonant tunneling spectroscopy



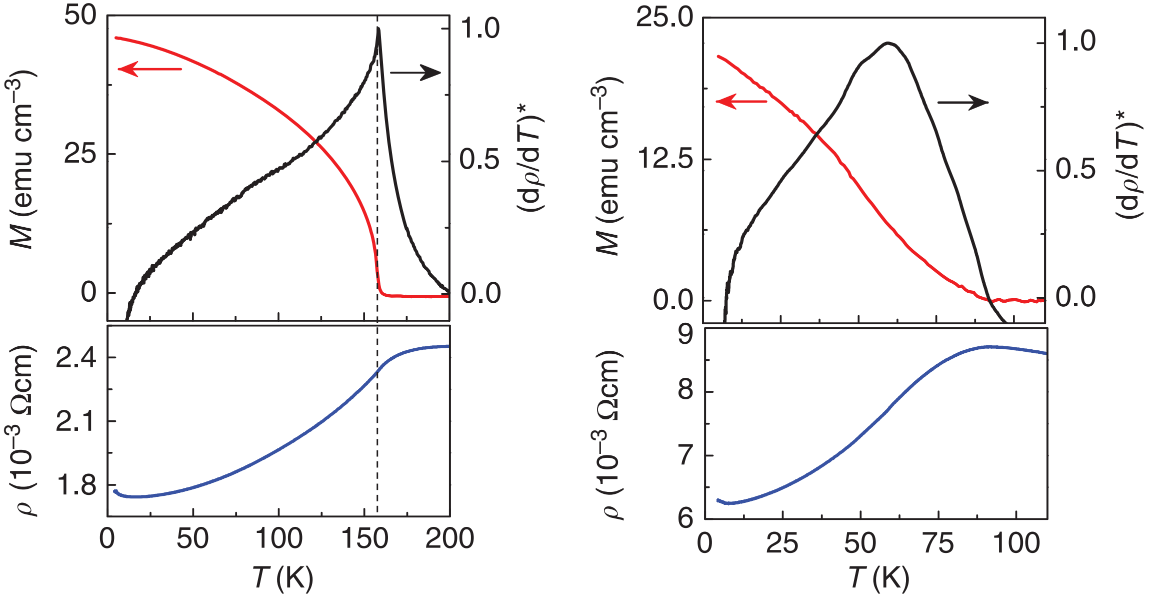






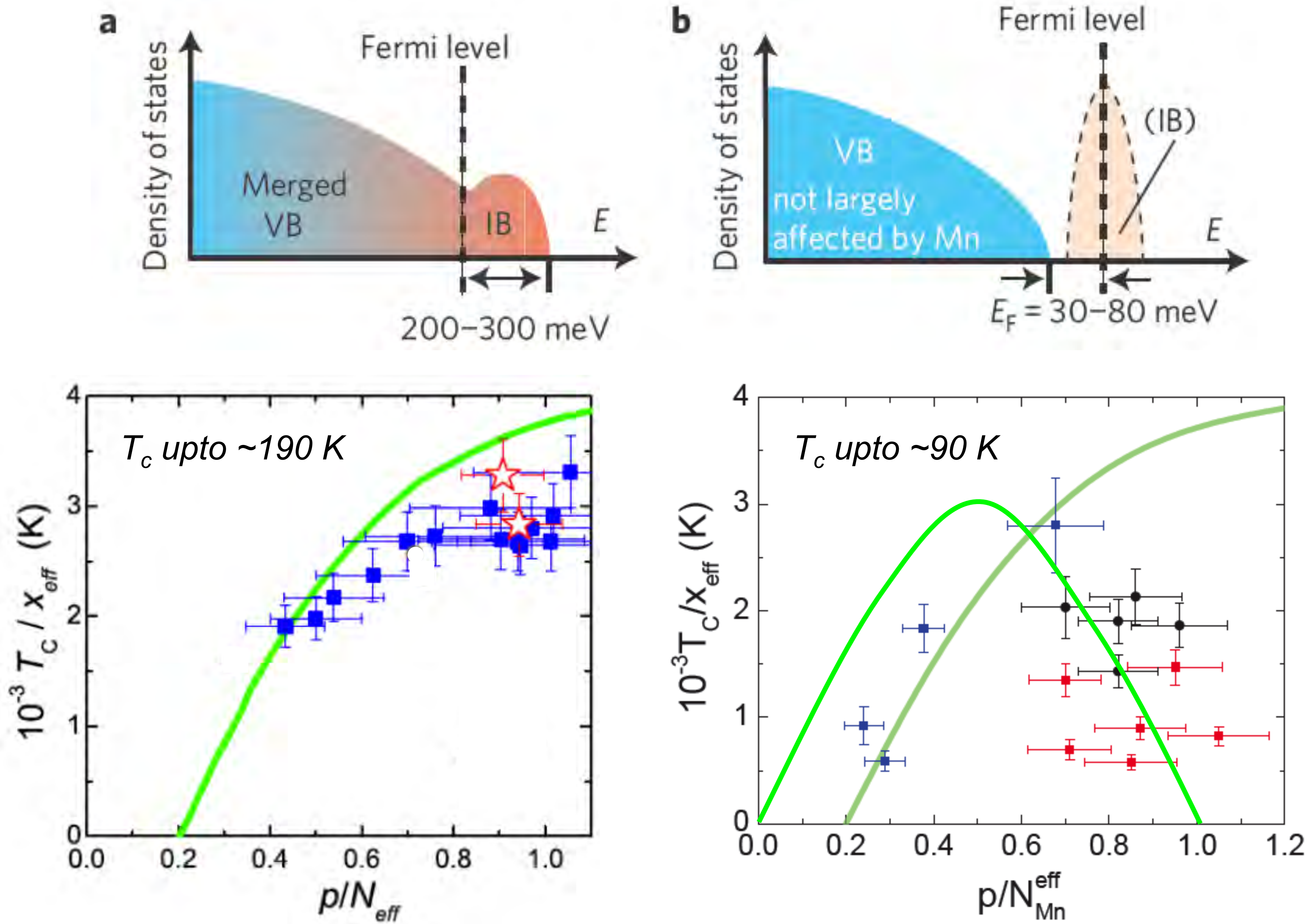
Ohya et al., Nature Phys. '11

Optimized synthesis of (Ga,Mn)As



Nemec et al. Nature Commun. '13

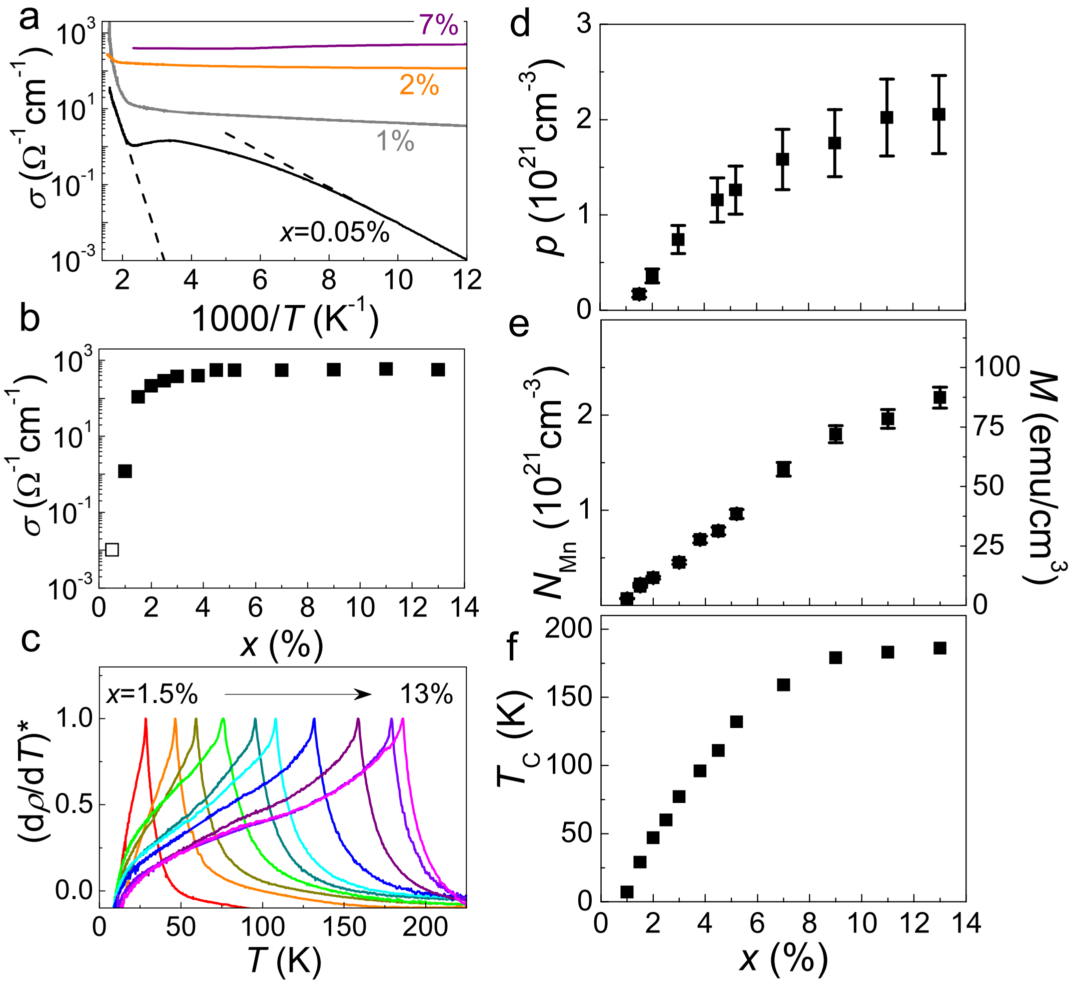
Curie temperature



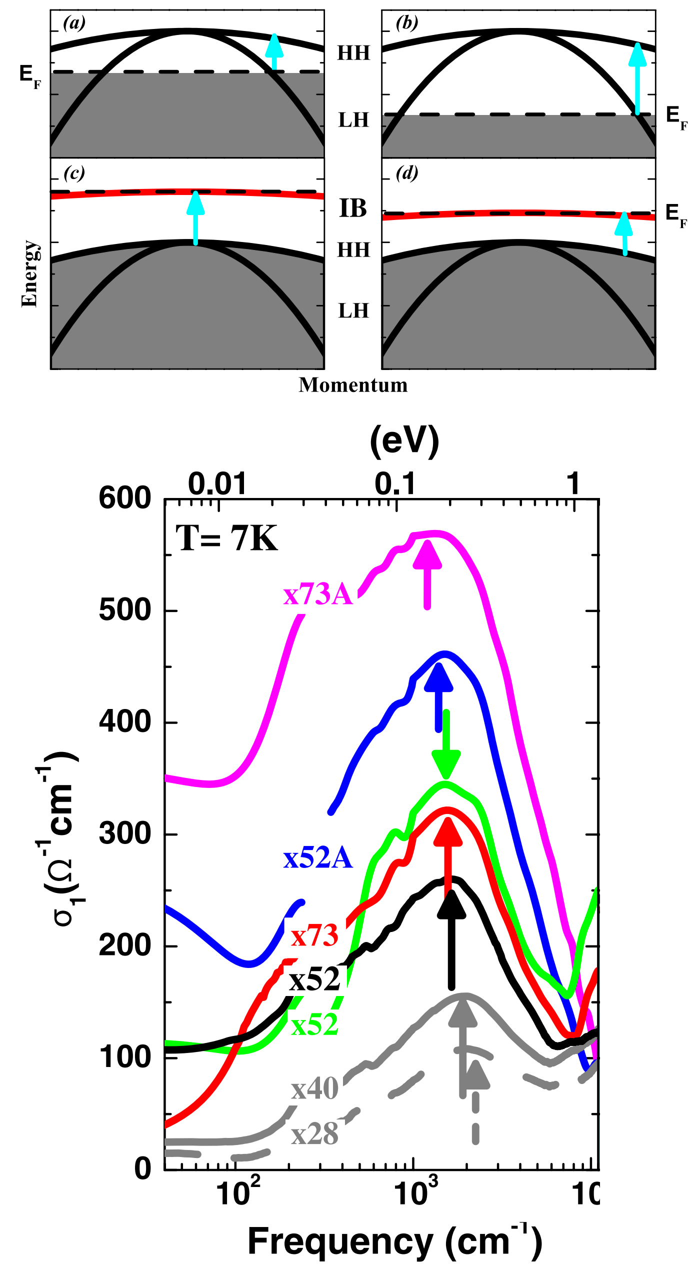
Wang et al. PRB '13

Dobrowolska et al. Nature Mat. '12

Infrared absorption

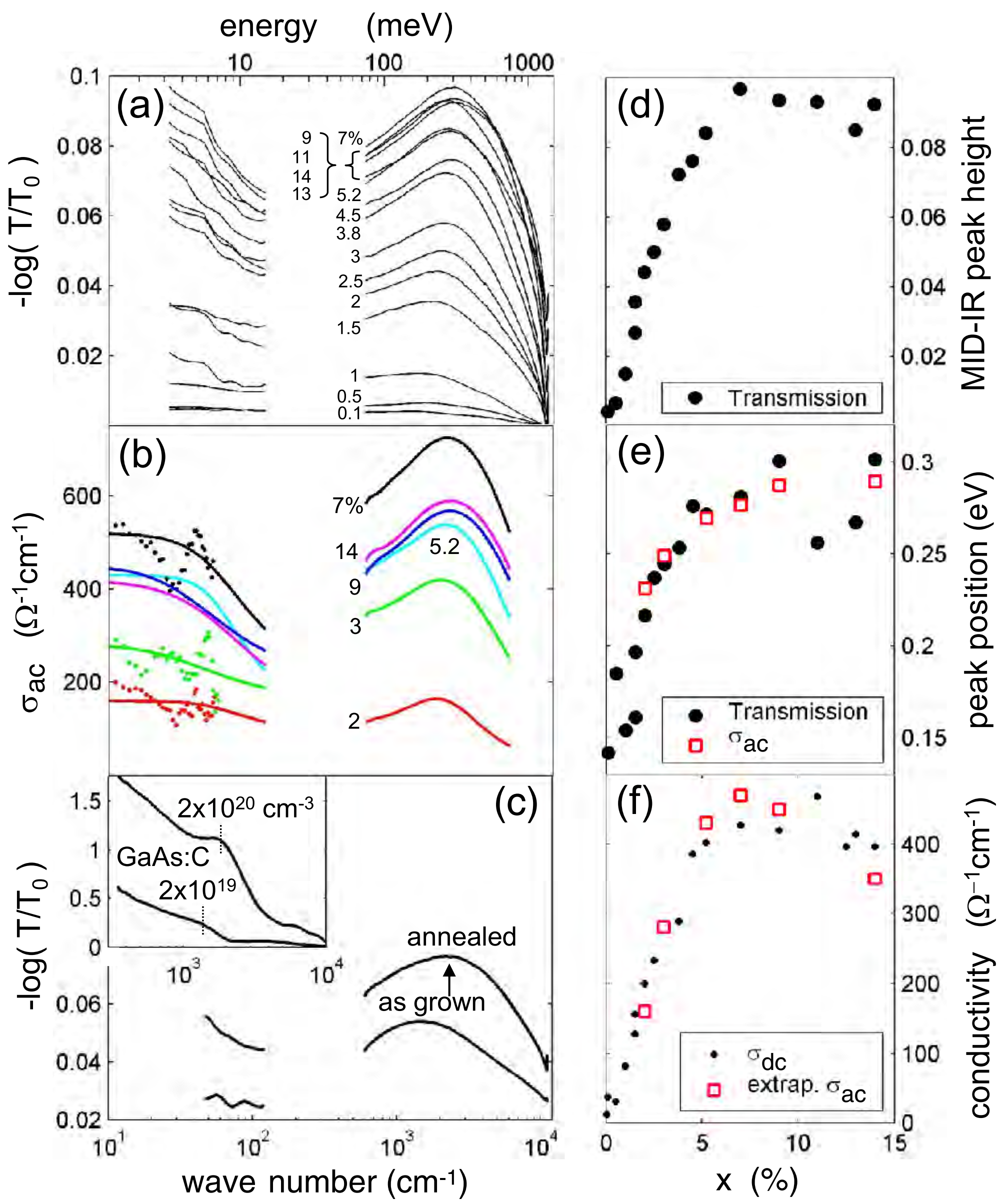


TJ et al. PRL'10

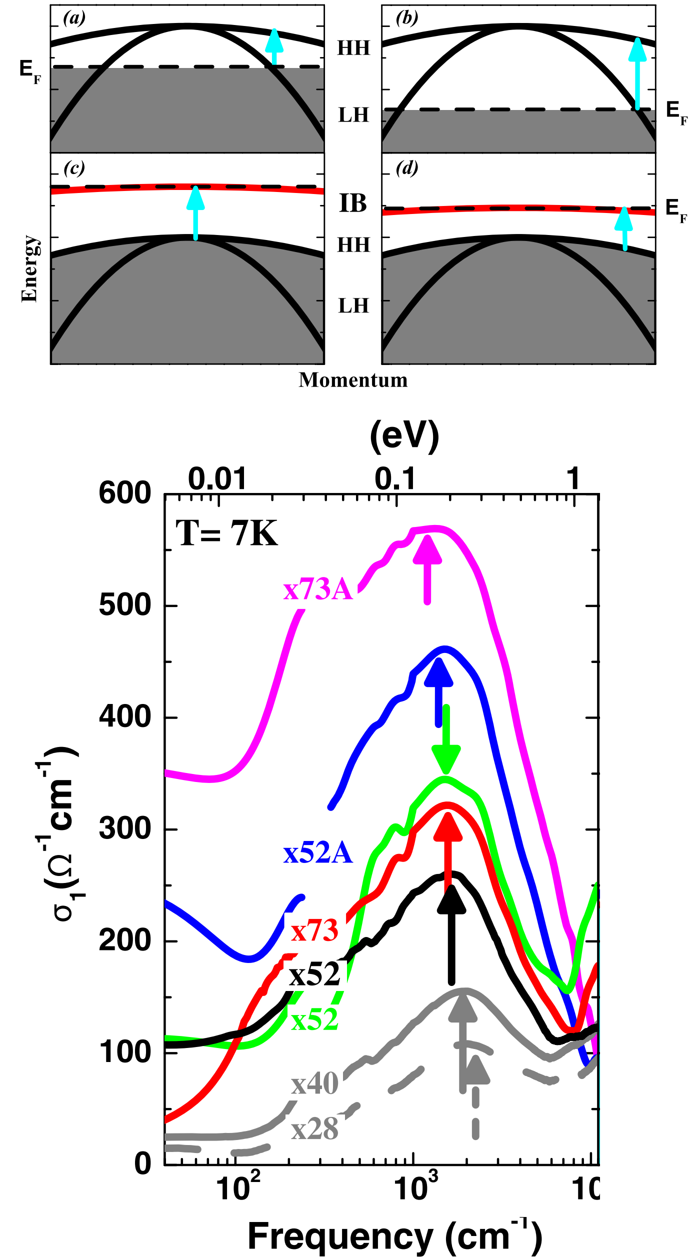


Burch et al. PRL ’06

Infrared absorption



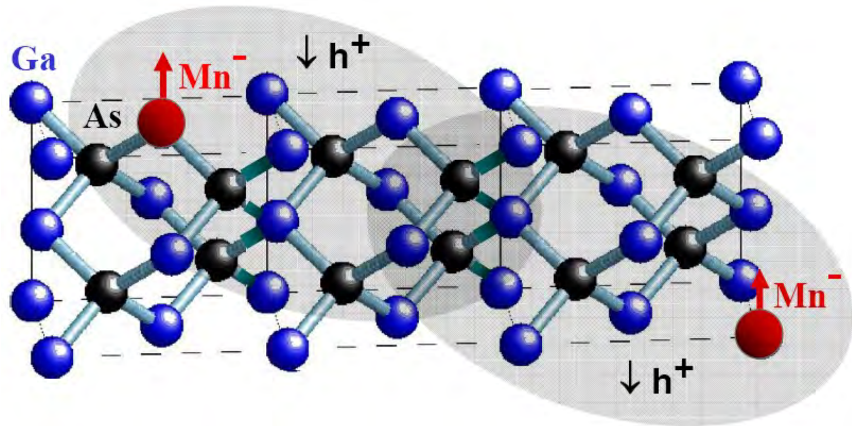
TJ et al. PRL'10



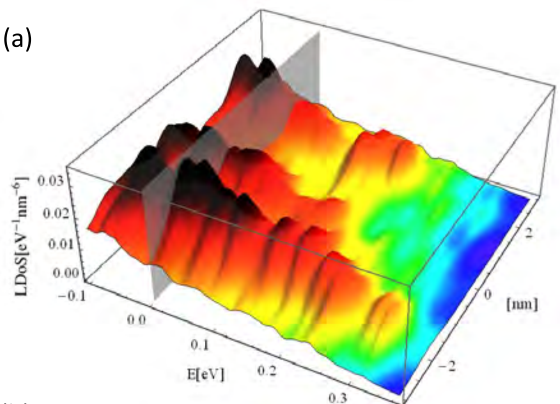
Burch et al. PRL '06

(Ga,Mn)As favorable model material for spintronics

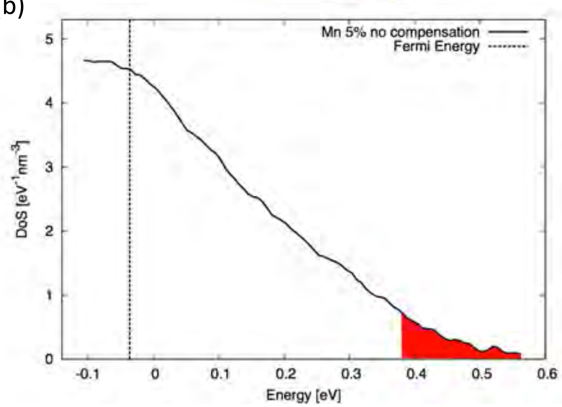
Strong intrinsic disorder (alloy rather than doped SC) → only qualitative/semiquantitave theory

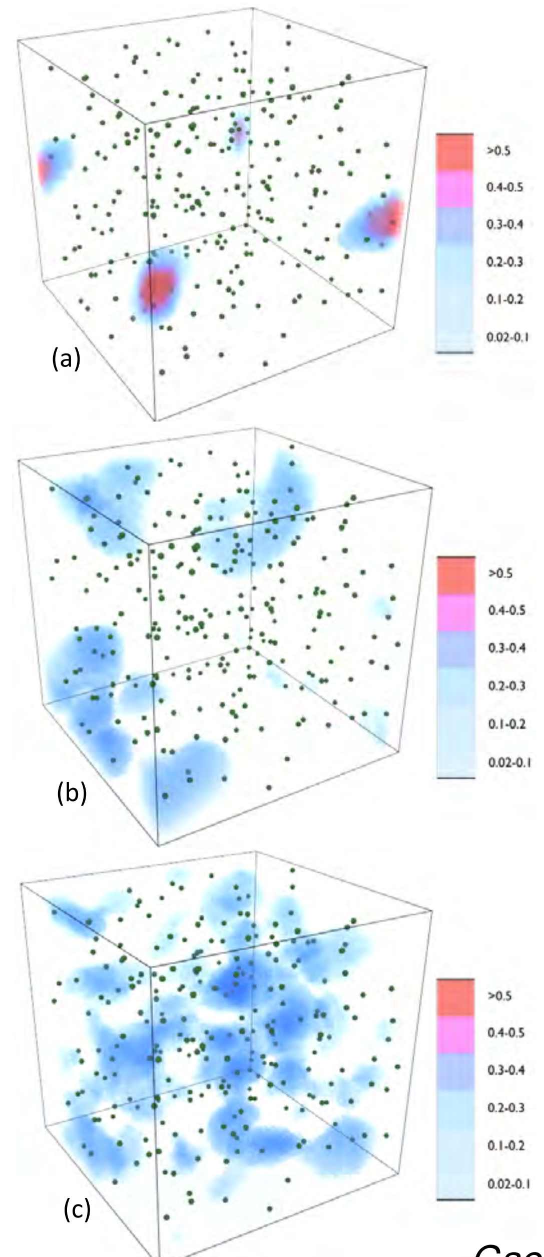


(a)



(b)

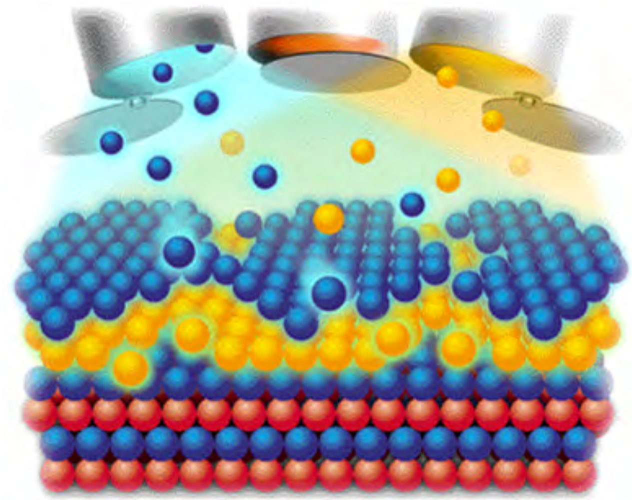




Gao et al. PRB'15

Magnetically-doped semiconductors

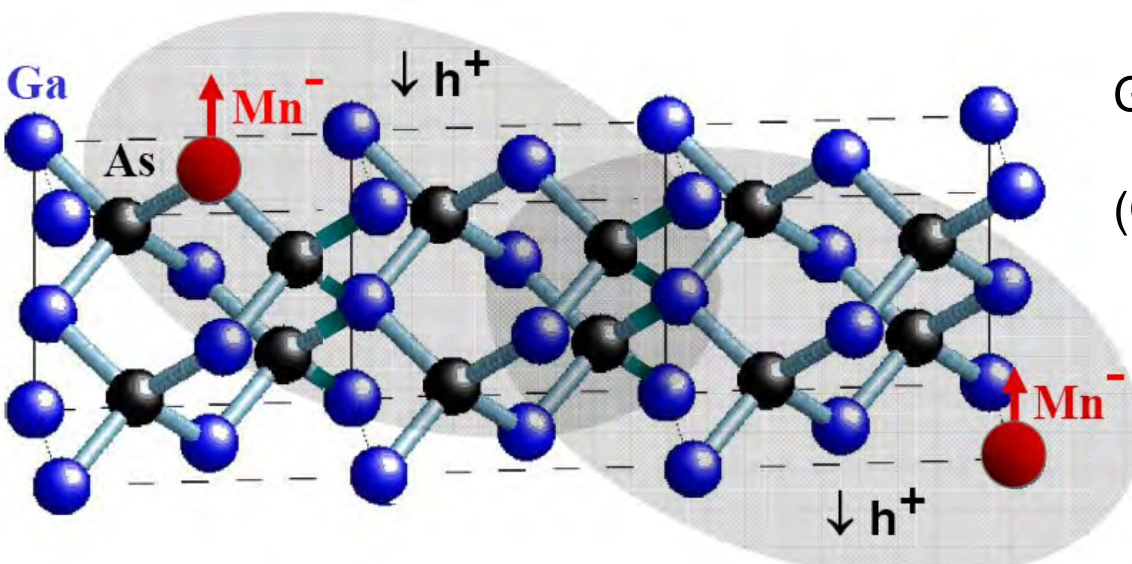
Molecular beam epitaxy of (Ga,Mn)As



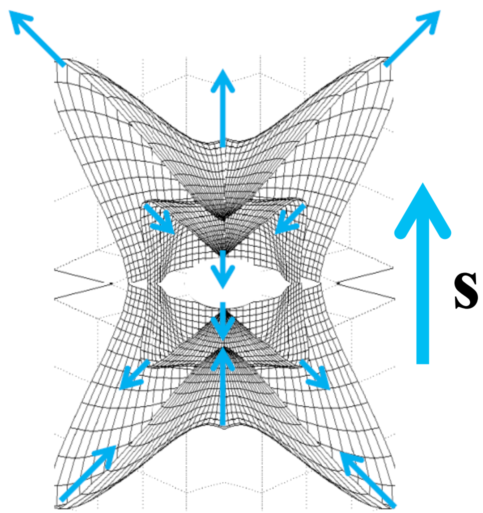
GaAs – common III-V semiconductor

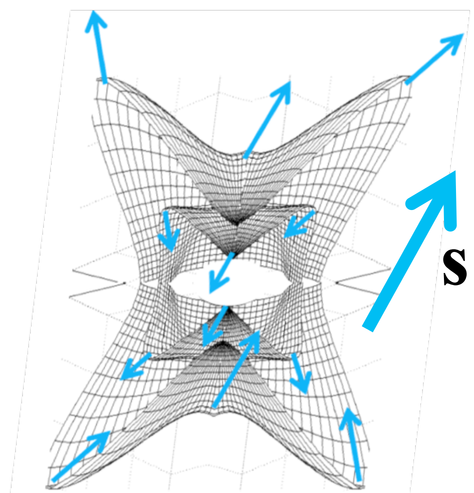
Group-II Mn – magnetic moment, hole

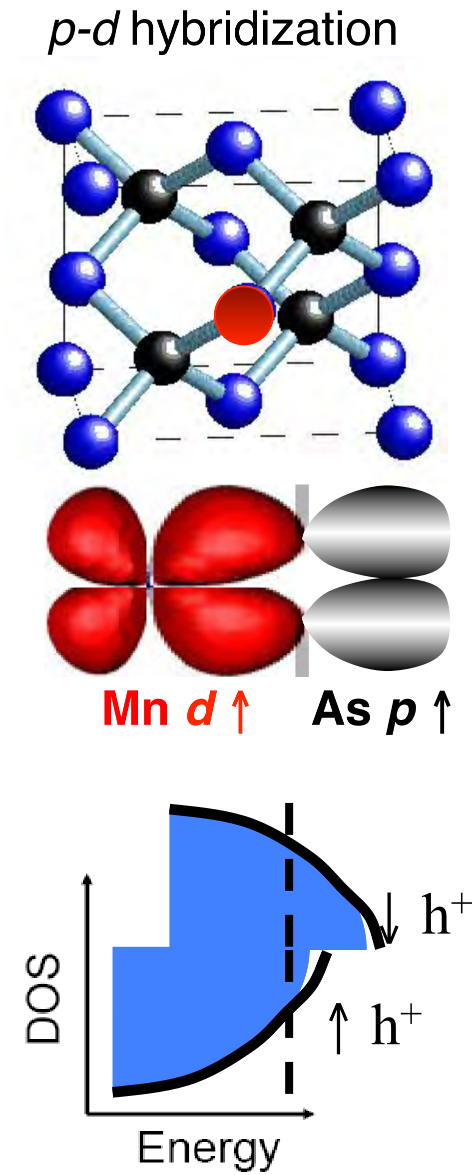
(Ga,Mn)As – feromagnetic semiconductor



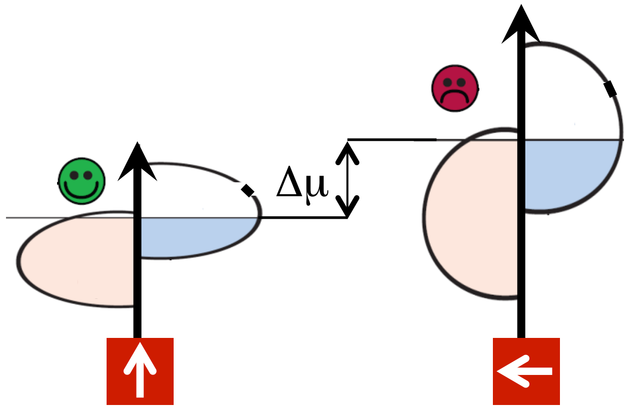
(Ga,Mn)As: magnetic anistropies







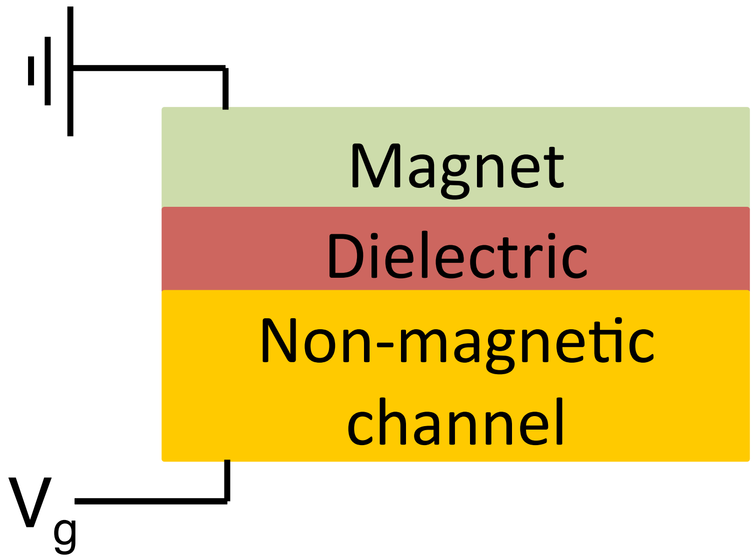
Spintronic device without current through magnet

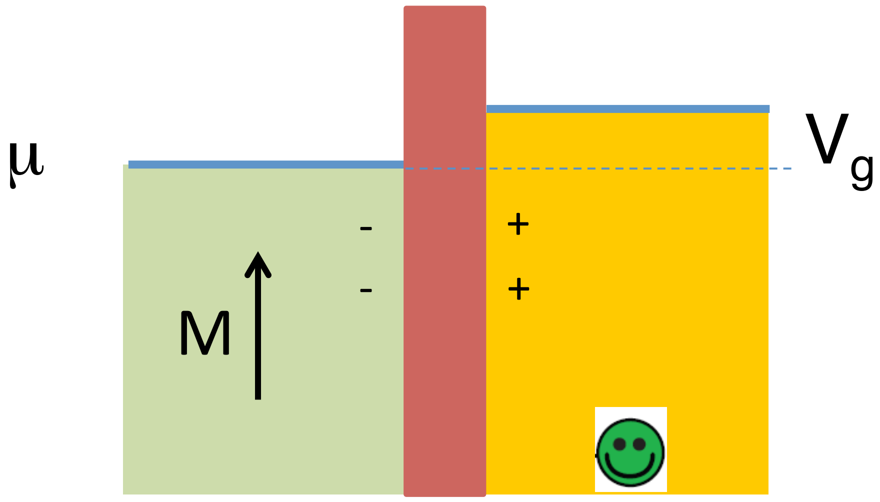


Chemical potential of magnetic gate changes

Charge on magnetic gate changes

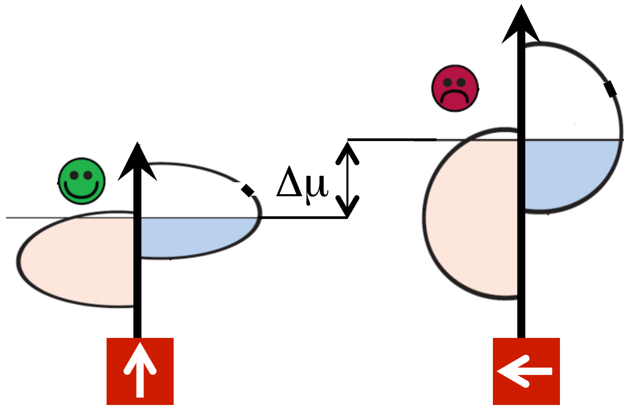
Polarisation charge on non-magnetic channel





Ciccarelli et al. APL '12

Spintronic device without current through magnet



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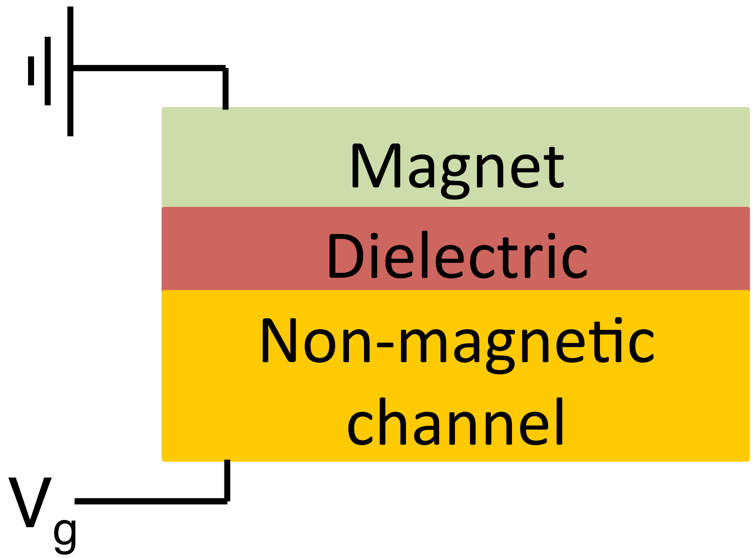
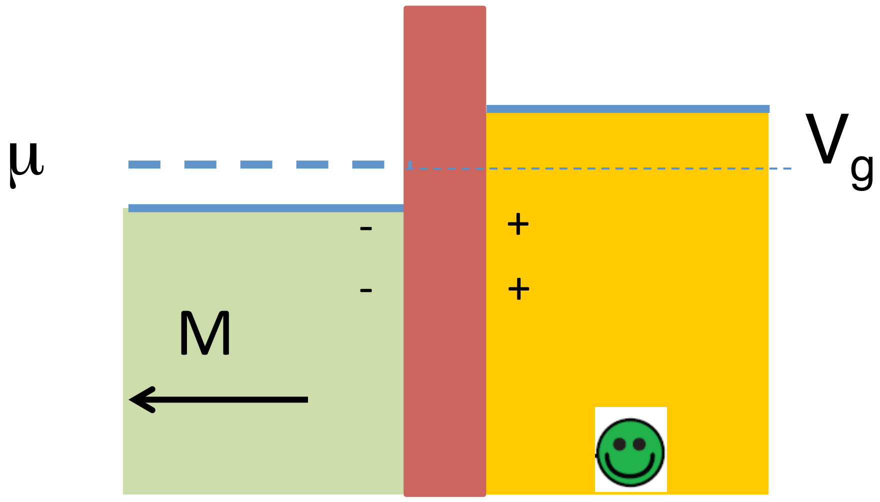
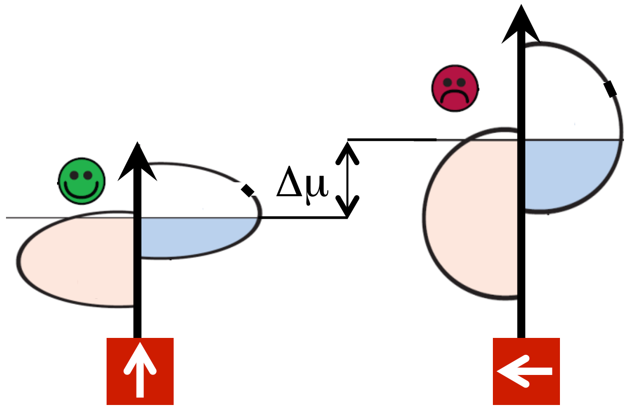




Ciccarelli et al. APL '12

Spintronic device without current through magnet



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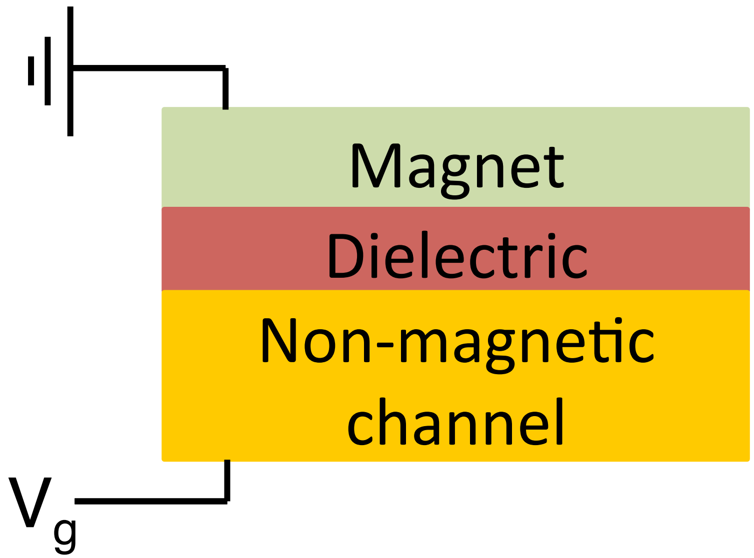
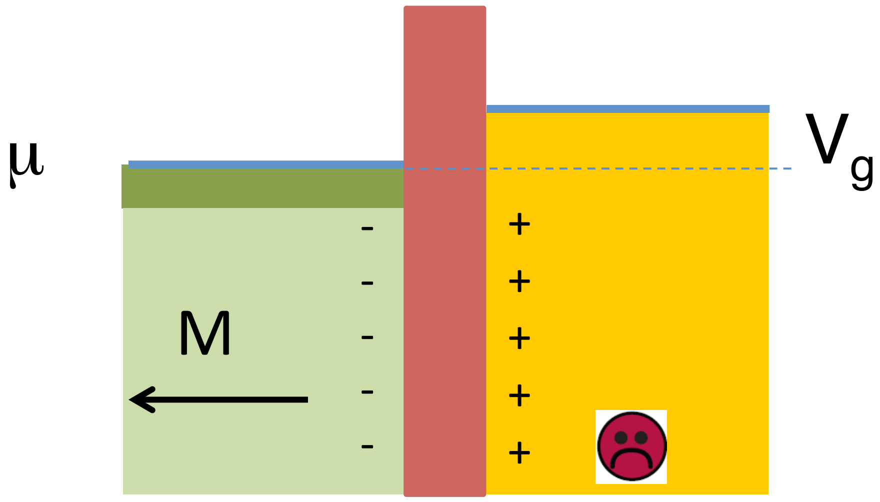
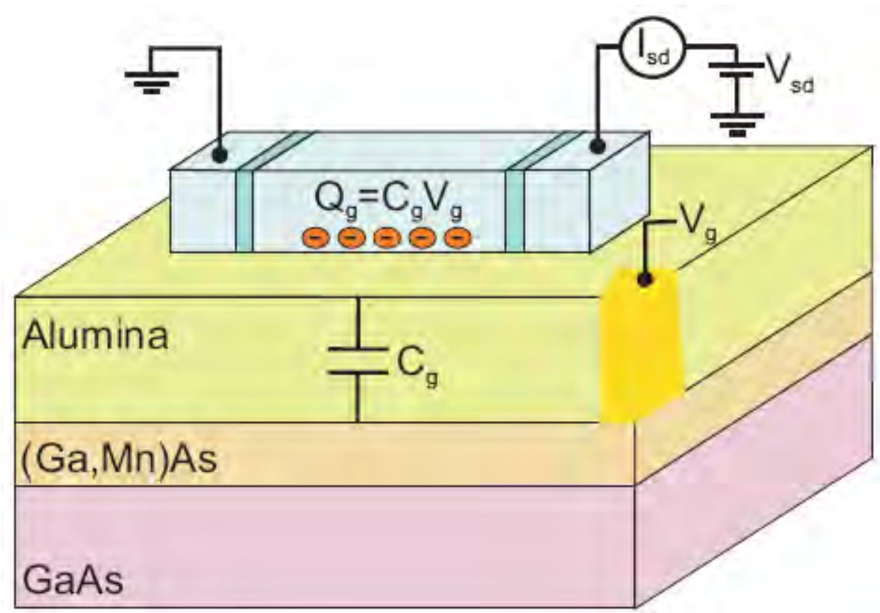
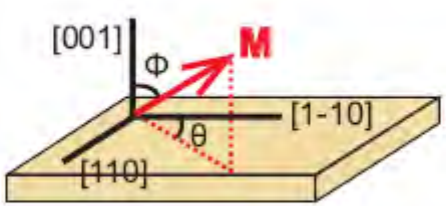


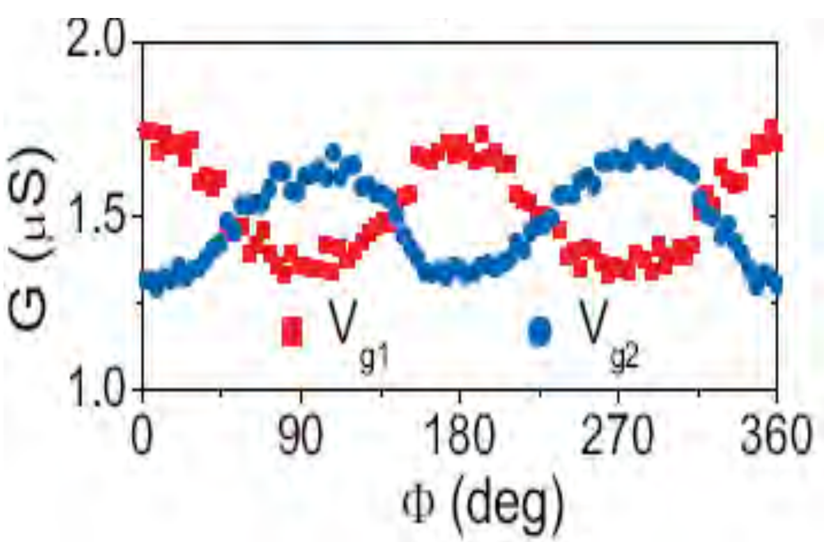


Ciccarelli et al. APL '12

Spintronic device without current through magnet

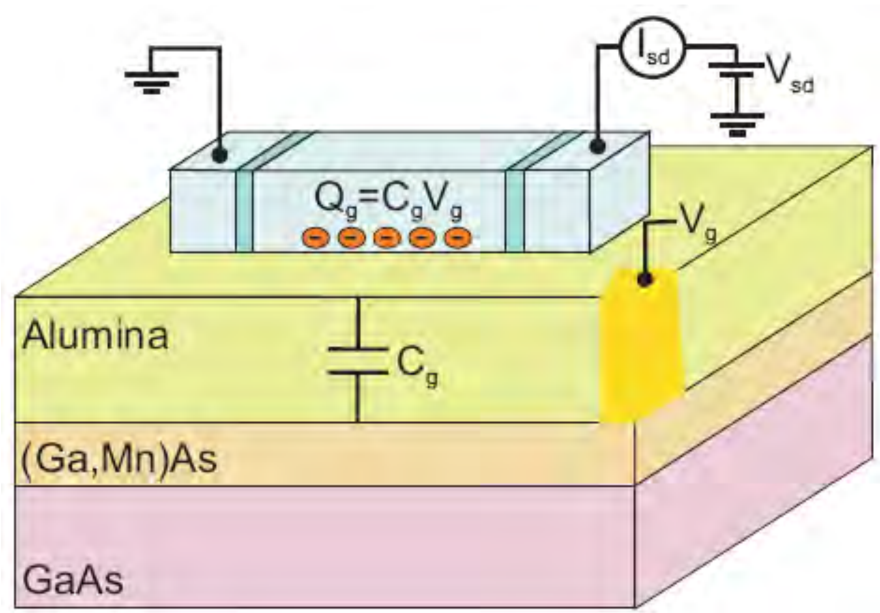






Ciccarelli et al. APL '12

Spintronic device without current through magnet



Spintronics

WIKIPEDIA

From Wikipedia, the free encyclopedia

Spintronics - a pormanteau meaning spin transport electronics ....

(Ga,Mn)As: Spintronics without spin transport

Ciccarelli et al. APL '12