Semiconductor Spintronics

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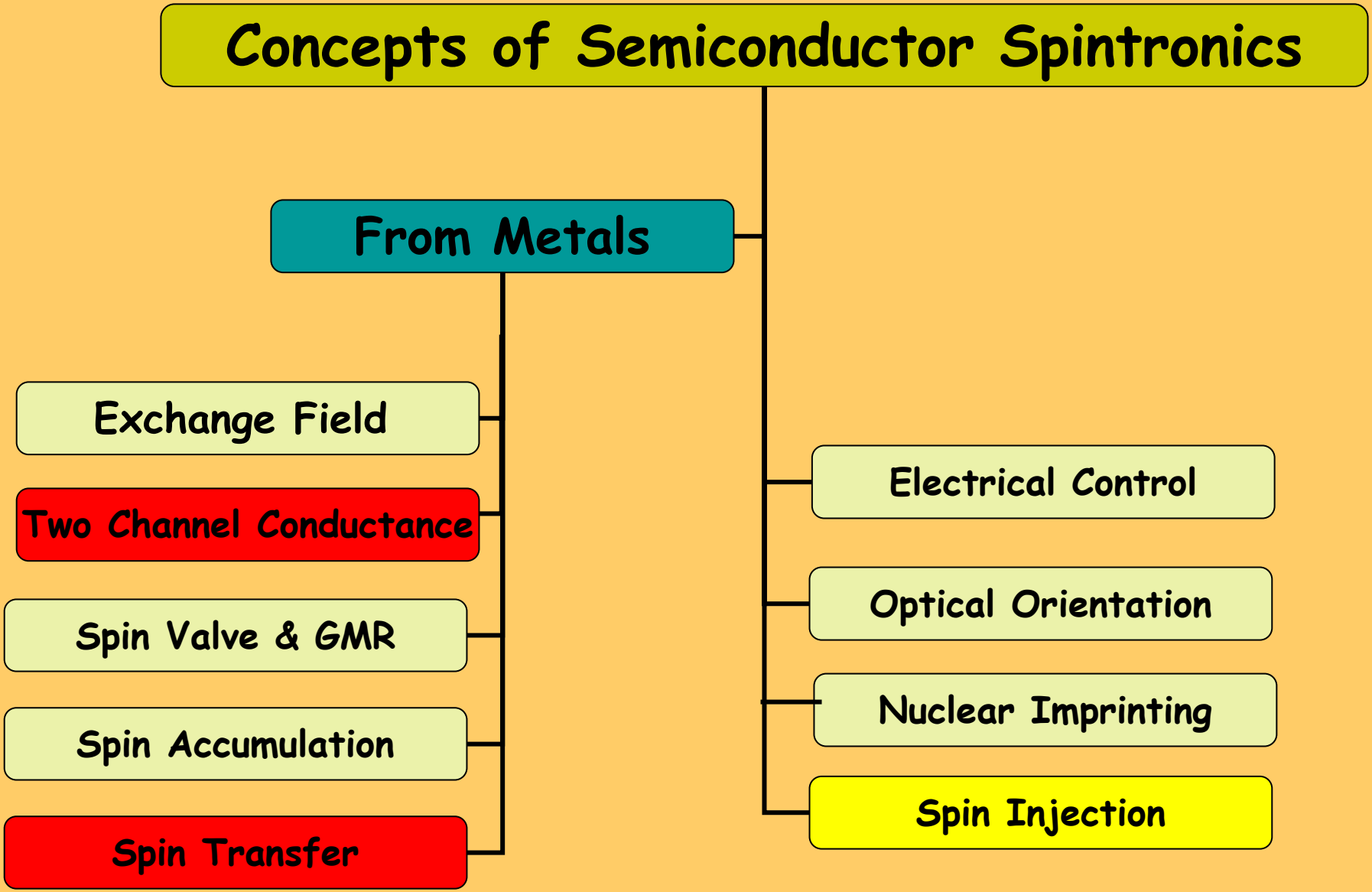
Disclaimer

These lectures reflect a personal point of view on an active and evolving research field. The coverage of topics is incomplete and unduly influenced by my current interests. For a wider guide to the literature, I suggest that you search cond-mat, PROLA etc. using key words from the 4th slide.

Lecture 1

Concepts of Spintronics


Concepts of Semiconductor Spintronics
From Metals
Exchange Field
Two Channel Conductance
Spin Valve & GMR
Spin Accumulation
Spin Transfer
Electrical Control
Optical Orientation
Nuclear Imprinting
Spin Injection

Spintronics Definition

Science of Electrical Devices in which transport properties can be altered by manipulating electronic spin states

Transition Metal Ferromagnets

Quasiparticles of ferromagnetic metals are electrons dressed by their interaction with the order parameter of the ferromagnet – the magnetization. They experience an extremely strong (~ 1eV) spin dependent Zeeman-like potential that lowers the energy of quasiparticles whose spin is aligned with the magnetization. We sometimes refer to these space-dependent potentials as spin-splitting fields. In a quantum theory they are dynamic quantum variables.

THE MAGNETIZATION DIRECTION IS VERY EASY TO MANIPULATE BECAUSE ANISOTROPY ENERGIES PER ELECTRON ARE VERY SMALL (~ 1μeV)

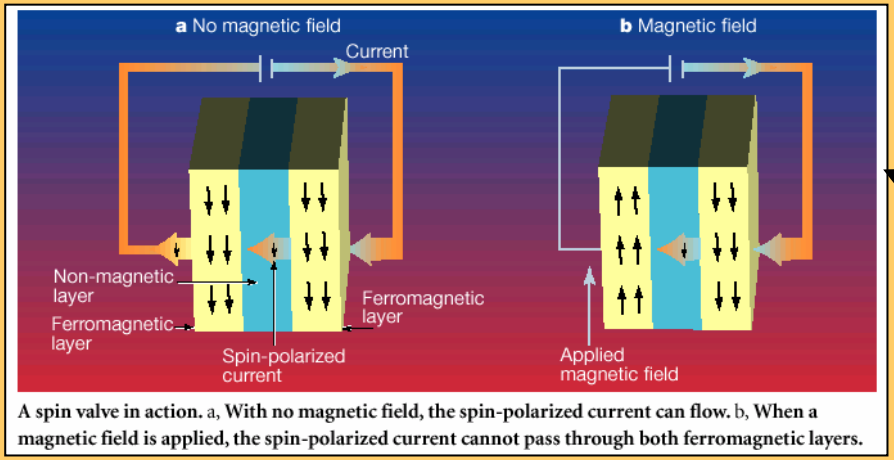
Giant Magnetoresistance (GMR)

Giant Magnetoresistance is a change in resistance due to a change in the magnetization orientation distribution in a system.

Resistance changes are often very large (giant) because the Zeeman potentials are so strong

The large changes of resistance occur in weak fields because of the (relatively) small anisotropy energies. They can occur very abruptly because the magnetization orientation usually behaves like a classical field that can be suddenly switched between distinct local-minimum configurations by tuning the system parameters through a stability region boundary.

Tunneling Magnetoresistance (TMR)



A spin valve in action. a, With no magnetic field, the spin-polarized current can flow. b, When a magnetic field is applied, the spin-polarized current cannot pass through both ferromagnetic layers.

IBM GMR Spin Valve

Tunneling Magnetoresistance is a special case of GMR in which current flows between two ferromagnets through a tunnel barrier. GMR usually requires that there be weak links in the magnetic coupling. In a spin-valve the magnetic weak link is created by a normal metal layer. A tunnel barrier can be advantageous, partially because it avoids loss of spin memory in the normal metal layer.

Two-Channel Conductor Model: Bulk

Many Metallic Ferromagnets have weak spin-orbit coupling; spin is nearly conserved. Because of the strong exchange correlation potentials the conductivity of majority and minority spin electrons in a ferromagnet are different, and the two quasiparticle systems carry spin nearly independently. The up and down spin currents are ,according to Ohm's Law, proportional to the up and down spin chemical potentials. Note the cross (drag) term which is present because of interactions between the quasiparticles but is normally weak and ignored.

$$
\begin{aligned}
j_\uparrow &= -\sigma_\uparrow \partial_x \mu_\uparrow - \sigma_{\uparrow,\downarrow} \partial_x \mu_\downarrow \\
j_\downarrow &= -\sigma_\downarrow \partial_x \mu_\downarrow - \sigma_{\downarrow,\uparrow} \partial_x \mu_\uparrow
\end{aligned}
$$

Two-Channel Conductor Model: Bulk

Scattering Prosses that can flip spins will bring the subsystems into local equilibrium. The net rate of spin transfer will be proportional to the local chemical potential difference.

$$\begin{aligned} \partial_t n_\uparrow + \partial_x j_\uparrow &= -C(\mu_\uparrow - \mu_\downarrow) \\ \partial_t n_\downarrow + \partial_x j_\downarrow &= C(\mu_\uparrow - \mu_\downarrow) \end{aligned}$$

$$\left.\frac{\partial \mu_s}{\partial n_{s'}}\right|_0 = [\mathcal{D}_{s,s'}]^{-1}$$

In linear response the chemical potentials (measured from their equilibrium values) are proportional to the partial densities (also measured from their equilibrium values. The linear relationship is specified by the system's thermodynamic density of states matrix.

Two-Channel Conductor Model: Bulk

These ingredients can be combined to derive an equation for the response of the magnetization to an external effective Zeeman field *h*. For a paramagnet the magnetiztion response decouples from the density response.

$$m = n_\uparrow - n_\downarrow$$

$$\partial_t m - \frac{\sigma - \sigma_D}{\mathcal{D}_{\uparrow,\uparrow} - \mathcal{D}_{\uparrow,\downarrow}} \partial_x^2 m + \frac{2C}{\mathcal{D}_{\uparrow,\uparrow} - \mathcal{D}_{\uparrow,\downarrow}} m = -2Ch + \frac{\sigma - \sigma_D}{\mathcal{D}_{\uparrow,\uparrow} - \mathcal{D}_{\uparrow,\downarrow}} \partial_x^2 h$$

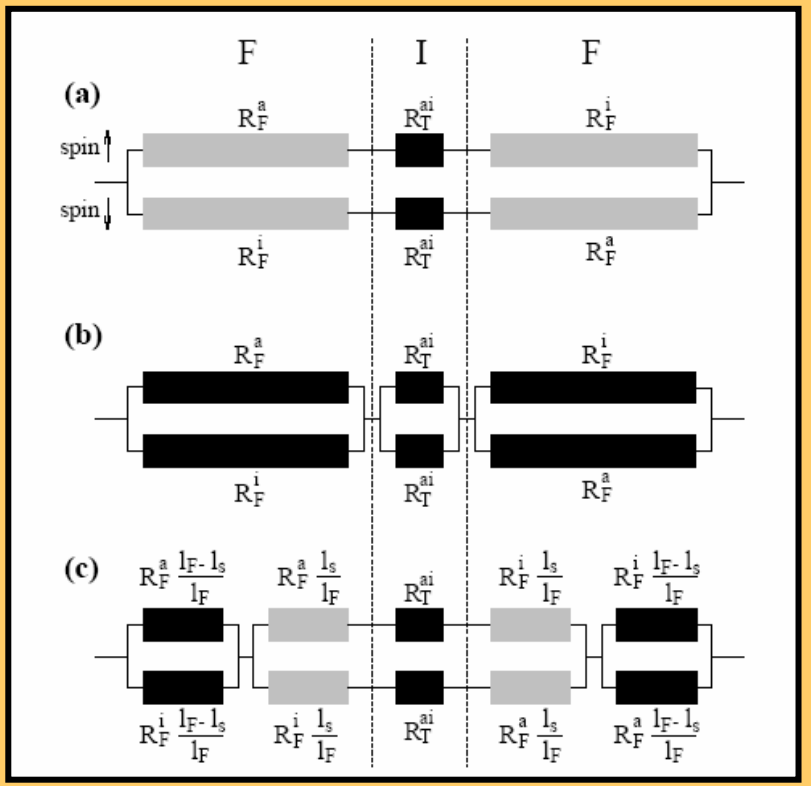
From this equation we can read off expressions for the length scale on which a steady-state magnetization goes to zero, and for the time scale on which a uniform magnetization goes to zero, in the absence of an external potential.

$$\tau_s = \frac{\mathcal{D}_{\uparrow,\uparrow} - \mathcal{D}_{\uparrow,\downarrow}}{2C}$$

$$\begin{aligned} L_s^2 &= \frac{\sigma - \sigma_D}{2C} \\ &= \frac{[\sigma - \sigma_D][\mathcal{D}_{\uparrow,\uparrow} - \mathcal{D}_{\uparrow,\downarrow}]}{\tau_s} \end{aligned}$$

Bulk GMR Mechanism

Bulk two-channel conductance is one mechanism for magnetoresistance. Up and down spin chemical potentials will always be different over the distance l_s (spin equilibration length) from any point at which the magnetization orientation changes. A good model is to imagine that the two channels are shorted together at a distance l_s from (for example) a tunnel barrier between two ferromagnets as in panel c) of the figure. You can easily verify the expression below for the resistance when the up spins are majority spins on one side of the barrier and minority on the other side - case A for antiparallel. The P (parallel) case gives a different resistance – usually smaller.



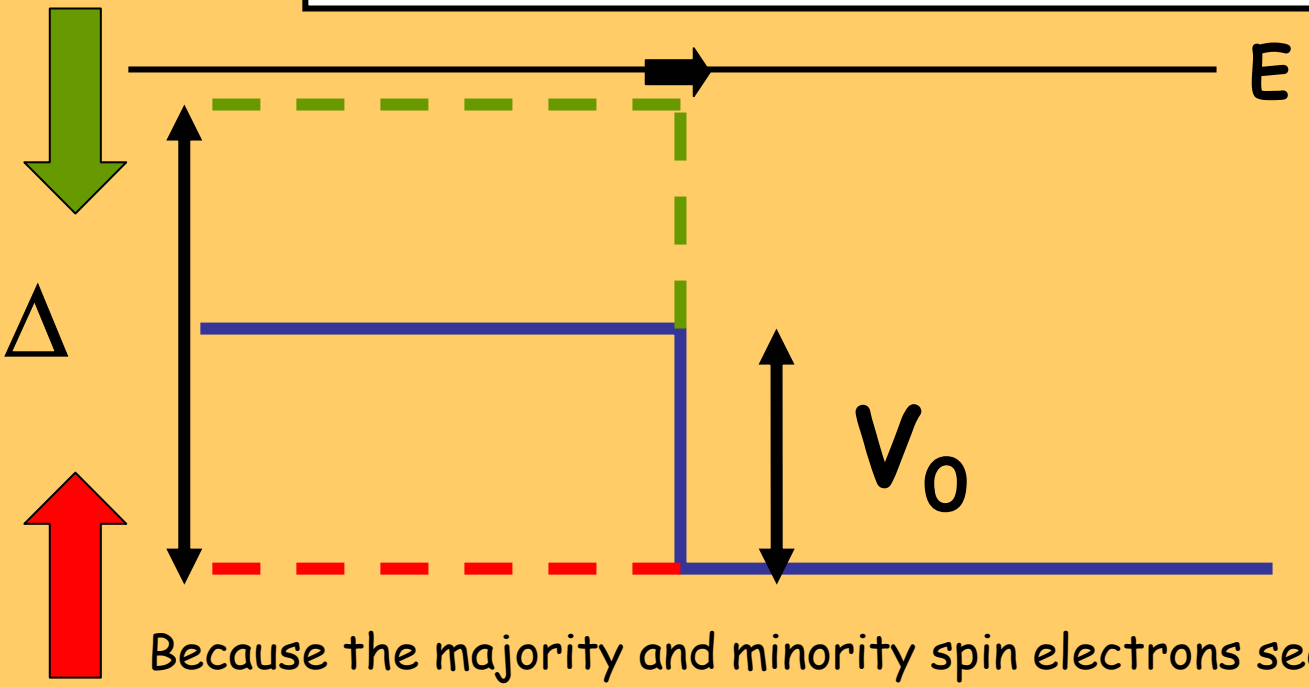
Jungwirth &AHM SSC 1997

$$R_J^A = 2\frac{R_F^a R_F^i}{R_F^a + R_F^i}\frac{l_F - l_s}{l_F} + \frac{1}{2}\left[\frac{l_s}{l_F}\left(R_F^a + R_F^i\right) + R_T^{ai}\right]$$

Interface GMR Mechanism

Majority and Minority Spin Band-Edge Profile

$$E = \hbar^2 k^2 / 2m^* = \hbar^2 k'^2 / 2m^* + V_0$$



$$T = \frac{4k'k}{(k+k')^2}$$

$$G = \frac{e^2}{h} \sum_{\vec{k}_\perp} T_{\vec{k}_\perp}$$

Because the majority and minority spin electrons see different potentials they will be scattered differently at a ferromagnet/normal-metal interface. In the case illustrated, the loss of the attractive exchange potential and the band offset cancel to give a completely flat majority spin potential.

Why semiconductors are better

Bloch Wilson

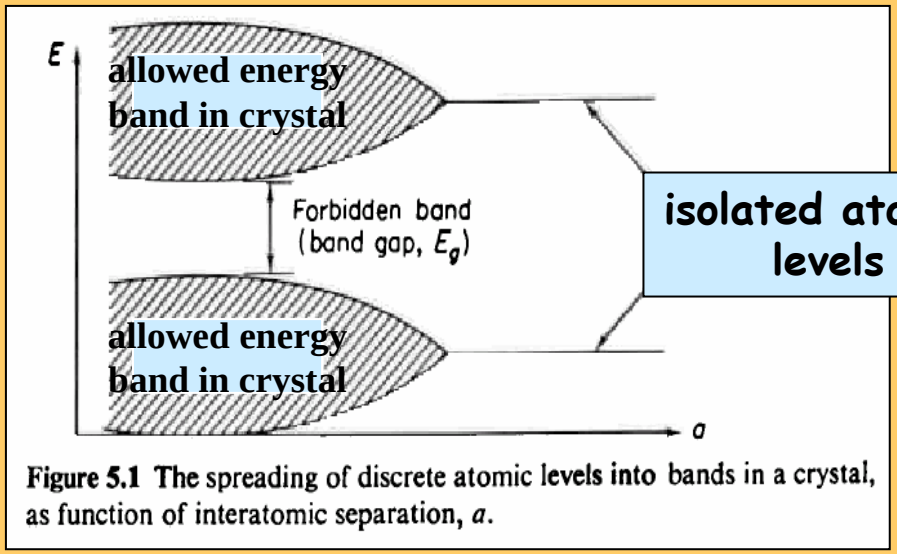


Figure 5.1 The spreading of discrete atomic levels into bands in a crystal, as function of interatomic separation, *a*.

Semiconductors are interesting because their properties are sensitive to impurities and to charges on external gates; they can be engineered

Pauli 1931: "One shouldn't work with semiconductors, that is a filthy mess; who knows whether they really exist"

What's Different in Semiconductors?

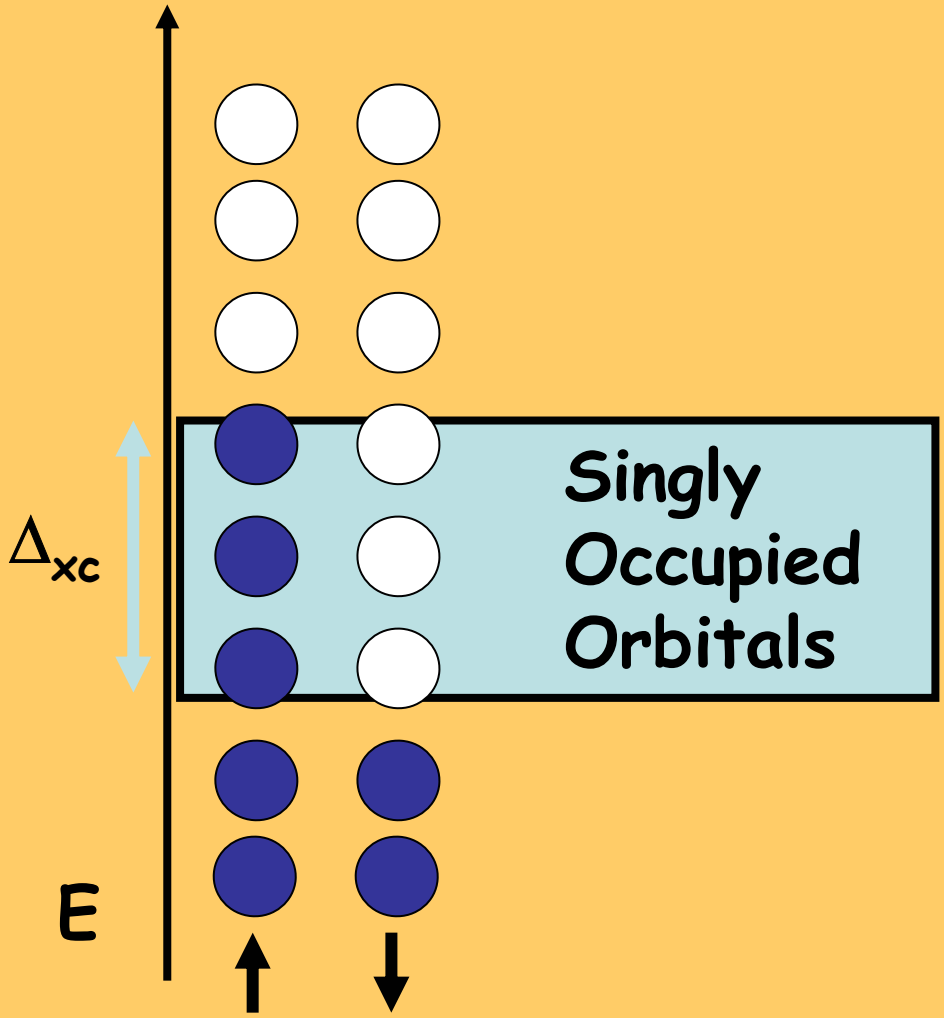
The Ferromagnetic semiconductors that we will discuss later have very strong spin-orbit coupling strength *relative to other energy scales like the Fermi energy.* The two-channel conductance model does not apply at all. GMR and TMR will still occur however. The key property that the total potential experienced by the quasiparticles, including the spin-dependent part, changes strongly when relative magnetization orientations change. Ferromagnetic semiconductors have interesting transport and optical properties because of strong SO-coupling.

Lecture 2

Models of Ferromagnetism

Quasiparticle
vs.
Collective
Dynamics

Itinerant Electron Ferromagnetism Cartoon



One successful picture of transition metal ferromagnetism is Density Functional Theory. In this theory the ground state has more orbitals of one (the majority) spin than the other (minority) spin occupied. The magnetism of the system is due to the singly occupied orbitals. The low energy collective magnetic excitations of the system (magnons) are ones in which the spinors of the singly occupied orbitals are all altered in the same way, or nearly the same way. The quasiparticles experience a large (Δ_{xc}) effective exchange-correlation Zeeman field that brings the two Fermi energies together.

Local-Spin-Density Theory

$$\mathcal{H} = \frac{p^2}{2m} + v_{eff}(\vec{r}) - \frac{1}{2}\vec{\Delta} \cdot \vec{\tau}$$

Kohn Sham Equations

$$\vec{\Delta}_{xc}(\vec{r}) = \frac{d\epsilon_{xc}(n,m)}{dm}\frac{\vec{m}}{|\vec{m}|}|_{m=m(\vec{r})}$$

Exchange-Correlation Potential Spin-Splitting Field (LSDA)

The Hamiltonian of the quasiparticles includes a Zeeman coupling term that originates primarily from interactions. In the LSDA the strength of this potential at a given point depends only on the spin and charge densities at that point. It acts like an effective magnetic field that points in the same direction as the magnetization. The total spin-density is obtained by adding the contributions from each quasiparticle. Dynamic solutions for the spin density are obtained by solving the time dependent quasiparticle (Kohn-Sham) Schroedinger Eq.

Quasiparticle Spin Dynamics

$$\chi^0_{xx} = \chi^0_{yy} = m_0 \frac{\Delta_0}{\Delta_0^2 - \hbar^2\omega^2}$$

$$\chi^0_{xy} = -\chi^0_{yx} = im_0 \frac{\hbar\omega}{\Delta_0^2 - \hbar^2\omega^2}$$

$$\Delta_0 = \Delta_{xc} + \Delta_{ext}$$

Spin-response Functions

The behavior of the quasiparticles is influenced by both external magnetic fields and by the exchange-correlation potential. A typical value of the magnitude of the exchange-correlation Zeeman potential is ~ 1eV. A typical external field, for example in a FMR experiment, is 4 or more orders of magnitude smaller. The simple response functions listed above apply when the Zeeman potential is independent of position. In this case orbital and spin-responses decouple and the above can be calculated by considering the case of a single-spin. The more realistic case requires a more detailed linear response calculation but gives a similar result.

Delta - Delta

In LSDA theory the magnetization is determined by summing over contributions from each quasiparticle state. When the quasiparticles respond to an external field the total spin-density changes and hence the exchange correlation potential. The quasiparticles respond both to the external field and to the change in the exchange correlation potential.

$$\delta\vec{\Delta} = \Delta_{xc}\,\frac{m_x\hat{x} + m_y\hat{y}}{m_0}$$

The above equation applies at each point in time and space. LSDA theory has the structure of a time-dependent mean-field theory but, because its potential is constructed from the magnetic fluctuation physics of an electron gas, captures the *exchange interaction* physics that favors locally and instantaneously aligned spins reasonably accurately. LSDA does not not capture the free energy contributions from long and moderate wavelength quantum or thermal spin-orientation fluctuations, which become important at finite temperature and actually limit the Ferromagnetic transition temperature.

Collective Spin Dynamics

$$
\begin{aligned}
m_x &= \chi_{xx}[\Delta_{1x} + \delta\Delta_x] + \chi_{xy}[\Delta_{1y} + \delta\Delta_y] \\
m_y &= \chi_{yx}[\Delta_{1x} + \delta\Delta_x] + \chi_{yy}[\Delta_{1y} + \delta\Delta_y]
\end{aligned}
$$

A little bit of algegra shows that when the change in the exchange correlation potential is accounted for, its contribution completely cancels out of the effective field that appears in the response function for collective magnetization fluctuations. In the model we have used, only the gap produced by the external magnetic field remains. In practice the collective dynamics is also influenced by magnetostatic interactions and by spin-orbit interactions which lead to magnetocyrstalline anisotropy.

When electrons in a ferromagnetic metal behave collectively they experience weak external magnetic fields and have slow dynamics.

$$
\begin{aligned}
\frac{1}{m_0}\left[(\Delta_0 - \Delta_{xc})m_x - im_0\hbar\omega m_y\right] &= \Delta_{1x} \\
\frac{1}{m_0}\left[im_0\hbar\omega m_x + (\Delta_0 - \Delta_{xc})m_y\right] &= \Delta_{1y}
\end{aligned}
$$

Auxiliary Field Path Integral

An important point of view on itinerant electron ferromagnetism arises from considering formal manipluations that can be carried out for simple model Hamiltonians, for example the simplest possible model in which Coulomb interactions are represented by a term in the Hamiltonian that lowers the energy of states with larger total spin-quantum numbers. In a path integral this attractive *perfect square* Hamiltonian can be represented at each instant in time by using Gaussian integrals to introduce an auxiliary Zeeman field h that is integrated over. In somewhat more realistic models, interactions are local

$$Z = \mathrm{Tr}\left[\exp\left(- \beta \left[H_{1b} + (U/2N_A)\, S_{tot}\,(S_{tot}+1)\right]\right]\right]$$

and independent auxiliary fields are can be introduced at each point in space and time. The Hubbard model, for example, can be represented exactly in this way as described in detail in Fradkin's book (for example). These auxiliary fields play much the same role as the exchange-correlation fields that appear in LSDA-density-functional theory, except that they are quantum fields that fluctuate as a function of space *and time*. Equations much like LSDA equilibrium equations result when from a mean-field-approximation within this quantum field theory. The equivalent of time-dependent LSDA equations appear as semiclassical equations of motion in the field theory.

Auxiliary Field Path Integral

Although we don't know how to derive such a field theory rigorously starting from a realistic model with Coulomb interactions, it seems clear that the exchange-correlation potential of density-functional theory can be elevated to a quantum field. In fact this is more or less done, in one way or another, by many researchers who try to understand metallic ferromagnetism from first principles. Most routinely, the exchange-correlation field orientations on each atomic site are treated as classical fields in order to understand thermal fluctuations, critical temperatures etc. LSDA theory is used to evaluate the Hamiltonian of these classical fields from the underlying electron physics.

Hubbard-Stratonovich Transformation for Long Range Interaction Model at T=0

$$S = \int_0^\beta d\tau [\frac{\vec{h}\cdot\vec{h}}{2U} - \ln[\langle\Phi_0(\vec{h}_N)|\exp(-\epsilon H_{tot}(\vec{h}_{N-1})|\Phi_0(\vec{h}_{N-1})\rangle \times \ldots \times \langle\Phi_0(\vec{h}_1)|\exp(-\epsilon H_{tot}(\vec{h}_N)|\Phi_0(\vec{h}_N)\rangle]],$$

Action and one-body Hamiltonian with fluctuating spin-splitting field.

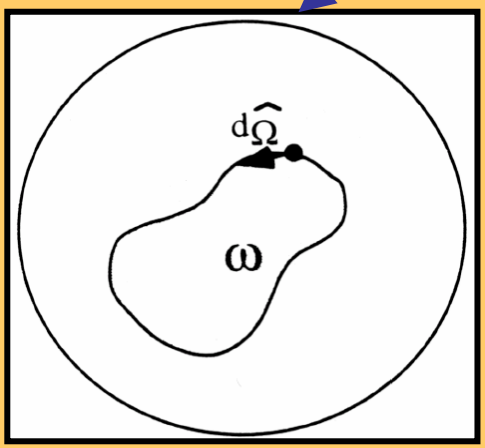
$$H_{tot}(\vec{h}) = H_{1b} + H_{so} - \frac{1}{2}\sum_{j,s',s}[\vec{h} + g\mu_B\vec{H}_{ext}]\cdot c^\dagger_{j,s'}\vec{\tau}_{s',s}c_{j,s}$$

Auxiliary Field Path Integral

$$S = \int_0^\beta d\tau \left[\langle \Phi_0(\vec{h}) | \partial \Phi_0 / \partial \vec{h} \rangle \cdot \frac{d\vec{h}}{d\tau} + E(\vec{h}) \right]$$

←Energy Term

Berry Phase Term



In this kind of path integral the exchange-correlation field direction plays the same role as the magnetiztion direction field that appears in the micromagnetic theory description of an itinerant electron ferromagnet. In fact the micromagnetic theory energy functional should be regarded as a partly phenomenological, realistic, energy functional for variations that are not too rapid on an atomic scale. We know that a description in terms of h alone breaks down for atomic scale variations for realistic systems, so micromagnetic theory is pretty much as good as we can do for this energy functional. In the quantum version of such a theory there is also a Berry phase term that expresses how the magnetic energy gets quantized. At long wavelengths this Berry phase is proportional to the spin-1/2 coherent state Berry-phase because the spins of all singly occupied orbitals behave collectively.

Gaussian Fluctuations & Perturbation Theory

$$S = \int_0^\beta \frac{N_A}{2U}\vec{\Delta}\cdot\vec{\Delta} - \ln\det(\partial_\tau + H_{1b}(\Delta^\alpha_{MF} + \tilde{\Delta}^\alpha)).$$

In a theory where the exchange-correlation Zeeman field appears a quantum field, the electrons can be *integrated out* since they enter the action only quadratically, to give a formal action in term of Δ alone, like the one above. In this simple case Δ is not allowed to have any position dependence, so this field corresponds to uniform magnetic fluctuations, coherent fluctuations in the micromagnetic language. This formula is useful mainly as the starting point for a quadratic (Gaussian) fluctuation expansion. The inverse of the Kernel of this quadratic action is the propogator for magnetic fluctuations. Its close relationship between the inverse LSDA response function is apparent by examining the expressions below. These different points of view should inform how we think about transition metal ferromagnetism.

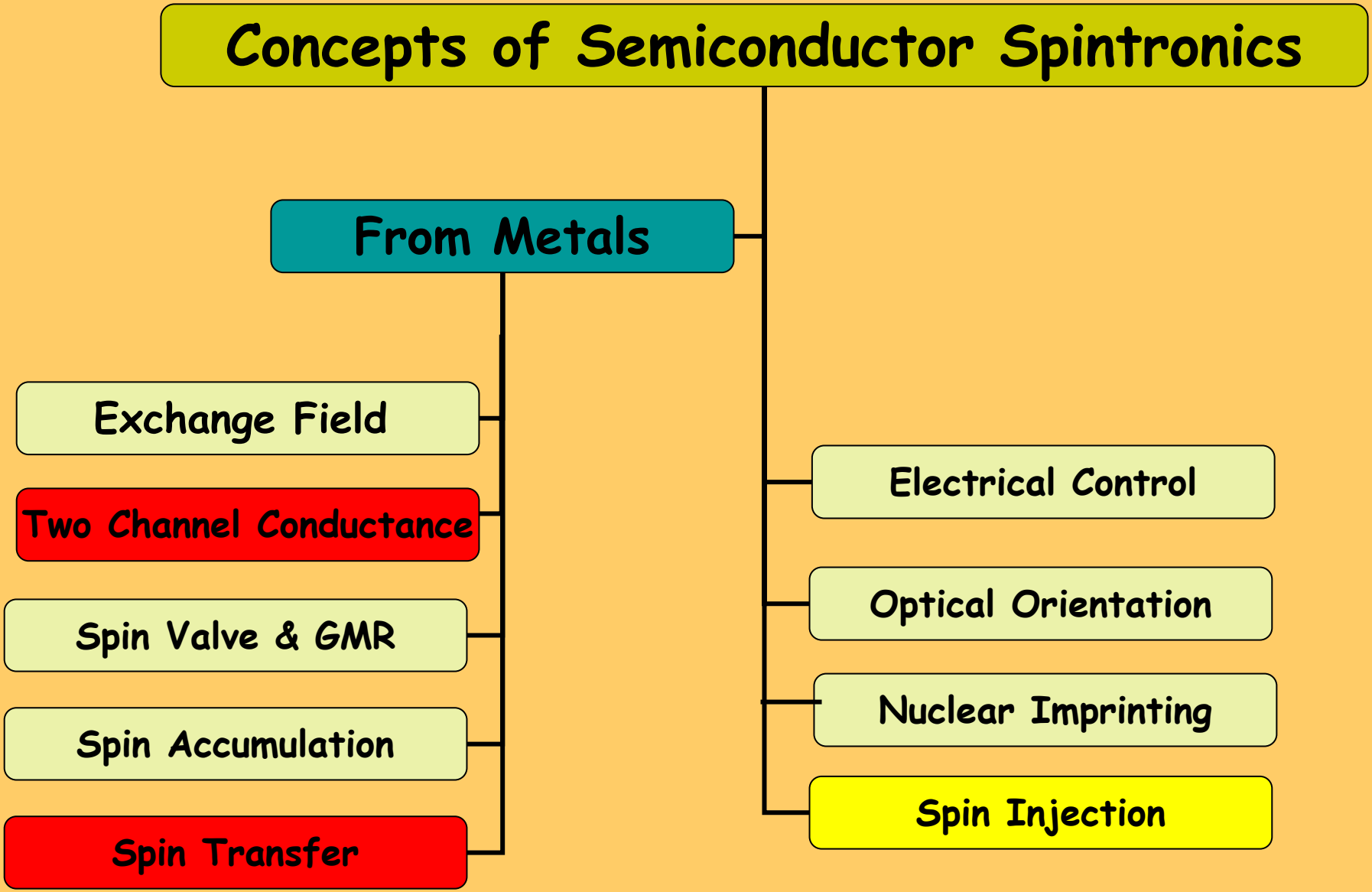
$$K^{\beta,\alpha}(i\Omega) = \delta_{\alpha,\beta}\frac{N_A}{U} + \sum_{I,J}\frac{n_F(\xi_J) - n_F(\xi_I)}{i\Omega + \xi_J - \xi_I}\langle J|s^\beta|I\rangle\langle I|s^\alpha|J\rangle.$$

$$K^{\pm,\mp}(i\Omega) = \frac{N_\uparrow - N_\downarrow}{\pm i\Omega - (\Delta + H_{ext})}$$

Lecture 3

Spin Transfer

DMS Ferromagnetism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Spin-transfer

From a theoretical point of view, spin-transfer phenomena, in which the order parameter field is manipulated by non-equilibrium quasiparticles are among the most interesting in spintronics. The basic ideas were proposed theoretically by Slonczewski and Berger. This class of phenomena have just started to be studied experimentally in the past few years, and many are not completely understood. Dan Ralph will review experiments and key theoretical ideas in this school. We will discuss spin-transfer at a conceptual level, within the framework of a LSDA type theory.

$$\frac{d\langle s_j(\vec{r})\rangle}{dt} = \nabla_i J^i_j + \frac{1}{2}\left[\vec{\Delta}\times\langle\vec{s}(\vec{r})\rangle\right]_j$$

A good starting point is the continuity equation above, which is satisfied by any solution of the time-dependent Kohn-Sham equations. It states that the time dependence of the spin-density at a given point in space has a contribution from spin-currents and a contribution from the precession of the quasiparticles in the total effective field that they experience. For time-independent solutions both left and right hand sides vanish. In equilibrium, no currents flow and the equilibrium spin-density must be parallel to the effective field at every point.

Spin-transfer

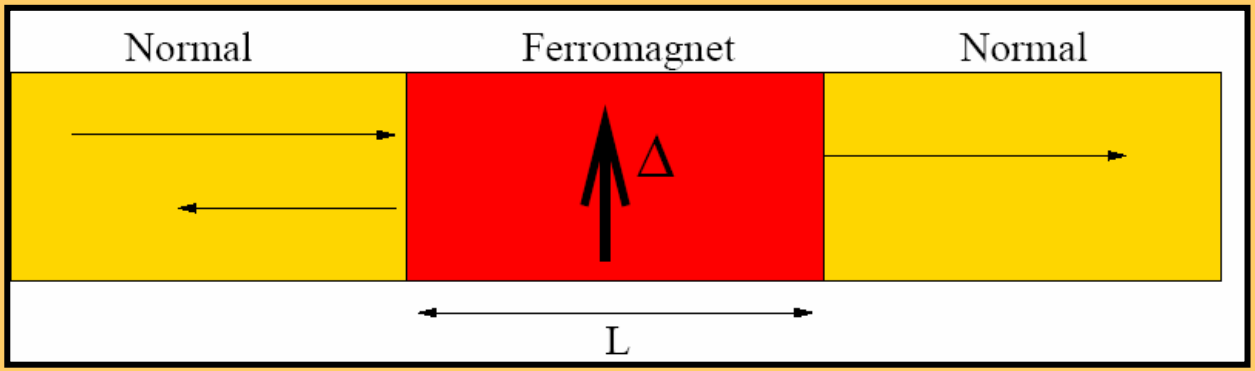
$$J_j^i = \frac{1}{2m}\mathrm{Im}\left(\Psi^\dagger(\vec{r})\tau_j\nabla^i\Psi(\vec{r})\right)$$

Spin Current

Spin Flux

$$\Gamma_j^{\mathrm{tot}} = \oint dS_i J_j^i$$

We assume that the quasiparticle Zeeman field has slow dynamics and solve the Kohn-Sham equations at each instant in time. In a Landauer transport theory only electrons in an energy interval of width eV near the Fermi energy will contribute to charge and spin currents. The dependence of their spin-current and spin-density distributions on bias voltage can be evaluated using standard techniques. Integrating the spin-continuity equation over a particular ferromagnetic element shows that the spin-flux is proportional to the average torque experienced by the quasiparaticles.



Spin-Transfer/ Delta-Delta

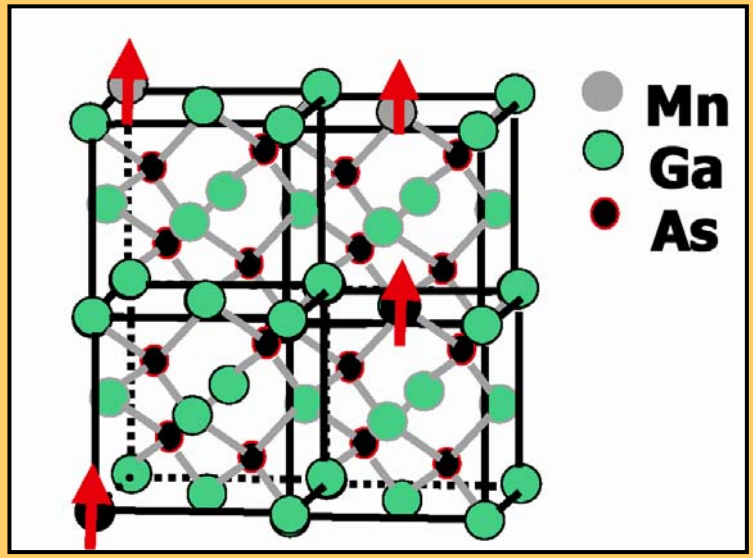
Spin-transfer is normally discussed in terms of the back-action of the torque that the exchange-correlation potential exerts on the quasiparticles, which must, it is argued, act on *the magnetization* to respect spin angular-momentum conservation. The consequences of non-equilibrium quasiparticle spins can be discussed more explicitly simply by recognizing that any component of the spin density that is perpendicular to the original orientation will result in an additional contribution to the effective magnetic field experienced by the quasiparticles; the *Delta-Delta we* discussed in the absence of a bias voltage earlier. This point of view is particularly useful when the terms in the Hamiltonian that do not conserve total spin are important – for example in Ferromagnetic semiconductors. Using this picture Alvaro Nunez, a school participant, has concluded that spin-transfer phenomena should occur even when spin-orbit interactions are strong.

$$\delta\vec{\Delta} = \Delta_{xc}\,\frac{m_x\hat{x} + m_y\hat{y}}{m_0}$$

Alvaro

Diluted Magnetic Semiconductor Ferromagnetism

It turns out that many (III,V) semiconductors like GaAs become ferromagnetic when Mn atoms are substituted for a relatively small fraction of the cations. I will conclude my lectures by making a few remarks about these ferromagnetic semiconductors. My thoughts about these materials have been formed while working on this topic together with a number of colleagues – most listed below – over the past several years.



Bill Atkinson, Ramin Abolfath, Dimi Culcer, Tomac Dietl, Joaquin Fernandez, Tomas Jungwirth, Juergen Koenig, Byounghak Lee, Qian Niu, Alvaro Nunez, John Schliemann, Jairo Sinova, Eric Yang

Ferromagnetic semiconductors web project

You can find a lot of information about (III,Mn)V ferromagnetic semiconductors at the web site whose url is given below. This web site was instigated by Tomas Jungwirth and is cared for by Jan Kucera Tomas, Jairo Sinova, and a number of other colleagues.

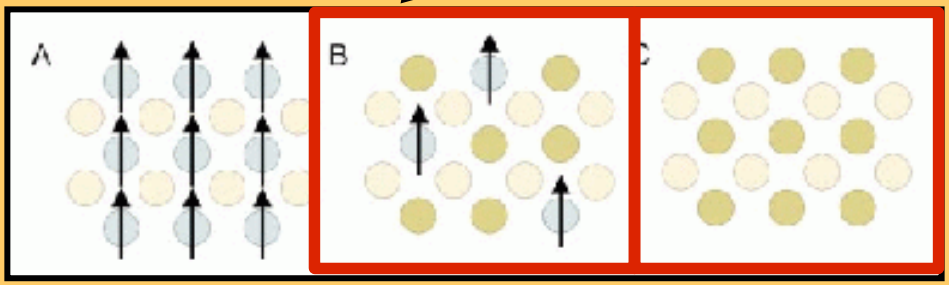
Tomas Junwirth

Jan Kucera

http://unix12.fzu.cz/ms

The Short Story

Diluted Magnetic Semis



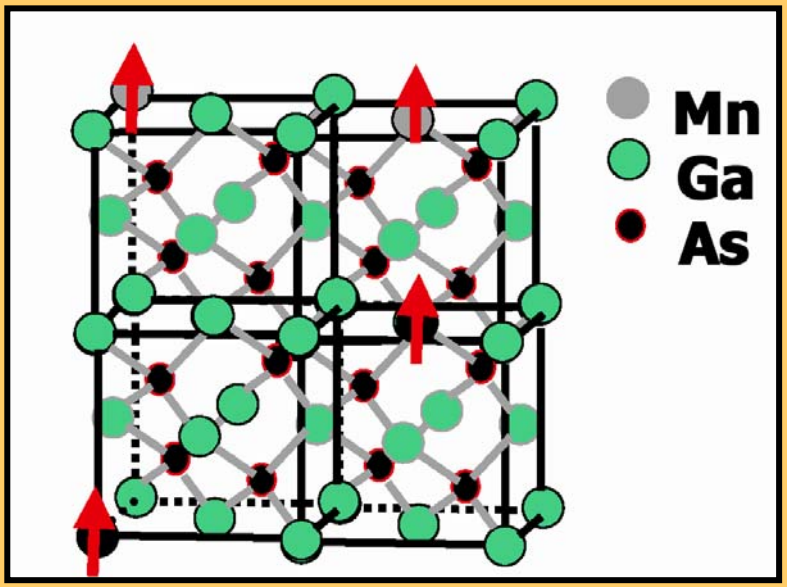
MANGANESE	54.938	
7.43	Mn	25
[Ar] $3d^5 4s^2$		
8.89	CUB	
1518		400

Hole-mediated ferromagnetism

Mn is an acceptor in (III,Mn)V

ZINC	65.38	GALLIUM	69.72	GERMANIUM	72.59	ARSENIC	74.922	SELENIUM	78.96
7.14	Zn 30	5.91	Ga 31	5.32	Ge 32	5.72	As 33	4.79	Se 34
[Ar] $3d^{10}4s^2$		[Ar] $3d^{10}4s^2 4p^1$		[Ar] $3d^{10}4s^2 4p^2$		[Ar] $3d^{10}4s^2 4p^3$		[Ar] $3d^{10}4s^2 4p^4$	
2.66	HEX 1.856	4.51	ORC 1.695 1.001	5.66	DIA	4.13	RHL 54°10′	4.36	HEX 1.136
693	234	303	240	1211	360	1090	285	490	150^{LT}
CADMIUM	112.40	INDIUM	114.82	TIN	118.69	ANTIMONY	121.75	TELLURIUM	127.60
8.65	Cd 48	7.31	In 49	7.30	Sn 50	6.62	Sb 51	6.24	Te 52
[Kr] $4d^{10}5s^2$		[Kr] $4d^{10}5s^2 5p^1$		[Kr] $4d^{10}5s^2 5p^2$		[Kr] $4d^{10}5s^2 5p^3$		[Kr] $4d^{10}5s^2 5p^4$	
2.98	HEX 1.886	4.59	TET 1.076	5.82	TET 0.546	4.51	RHL 57°6′	4.45	HEX 1.330
594	120	429.8	129	505	170	904	200	723	139^{LT}

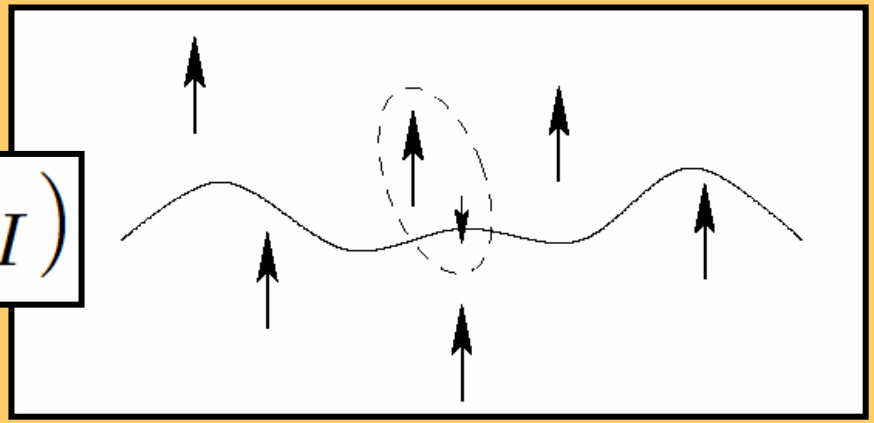
DMS Ferromagnetism



Mn = Local Moments + Holes

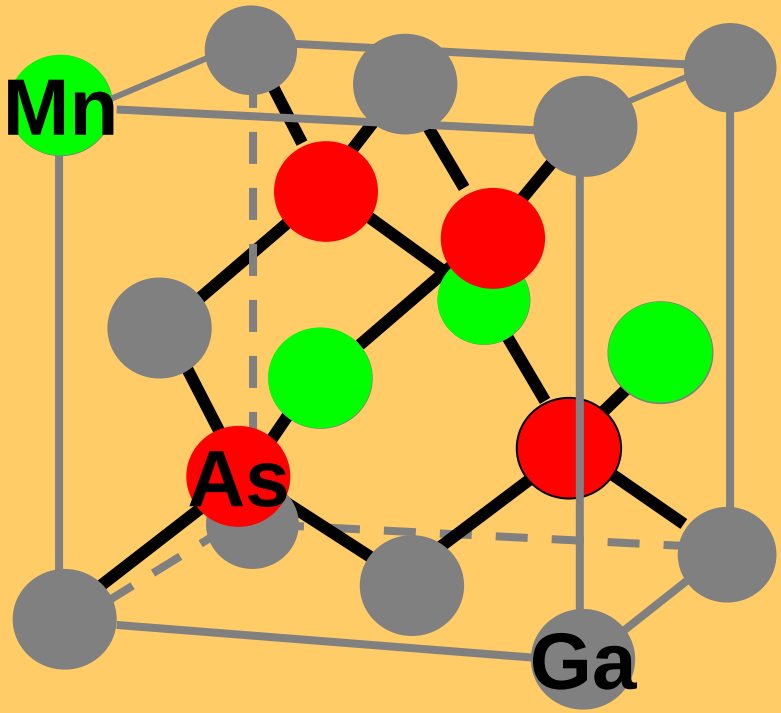
Mn substitution introduces both valence band holes and S=5/2 L=0 local moments as low energy degrees of freedom. The degenerate Fermi gas of holes couples the local moments and favors ferromagnetism at low temperatures.

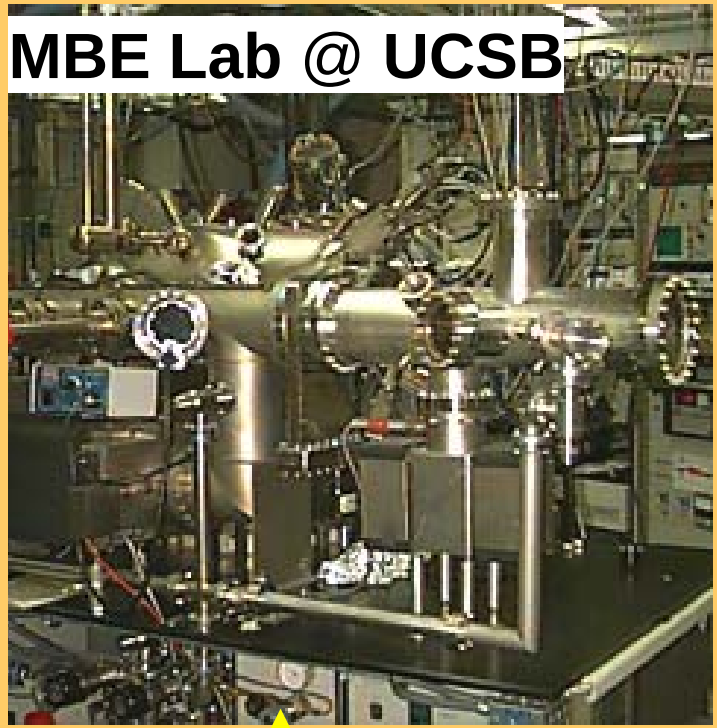
$$J_{\mathrm{pd}} \sum_I \boldsymbol{S}_I \cdot \boldsymbol{s}(\boldsymbol{R}_I)$$



The Dirty Low Down

(III,Mn)V ferromagnets can not be obtained by equilibrium growth techniques because the Mn atoms tend to cluster. They are usually grown by MBE. Unintended defects, particularly substitutional Mn atoms, are unfavorable for ferromagnetism. A lot of progress has been achieved by eliminating these defects by suitable annealing.



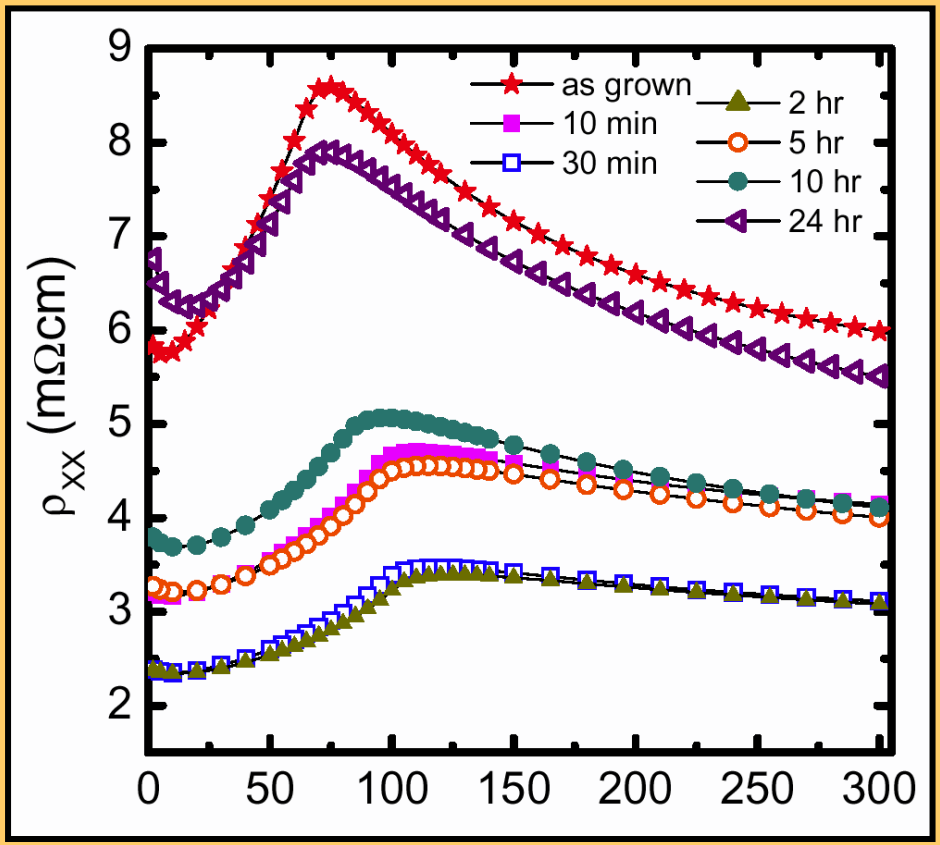


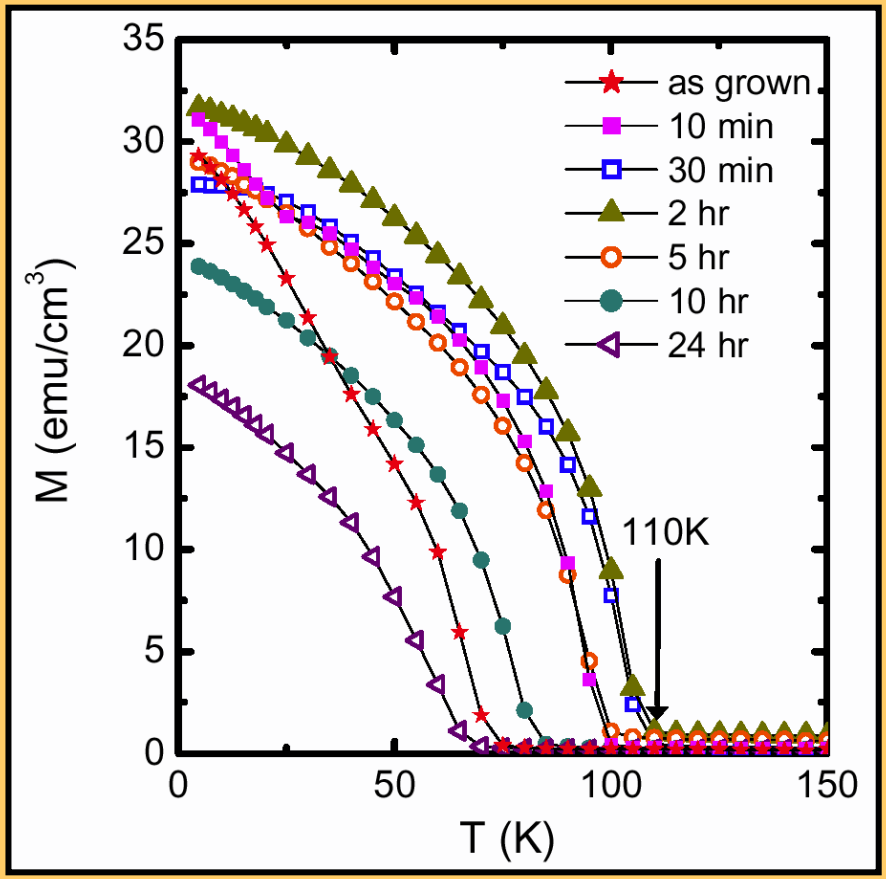
Ferromagnetic: x=2-7%

LT - MBE

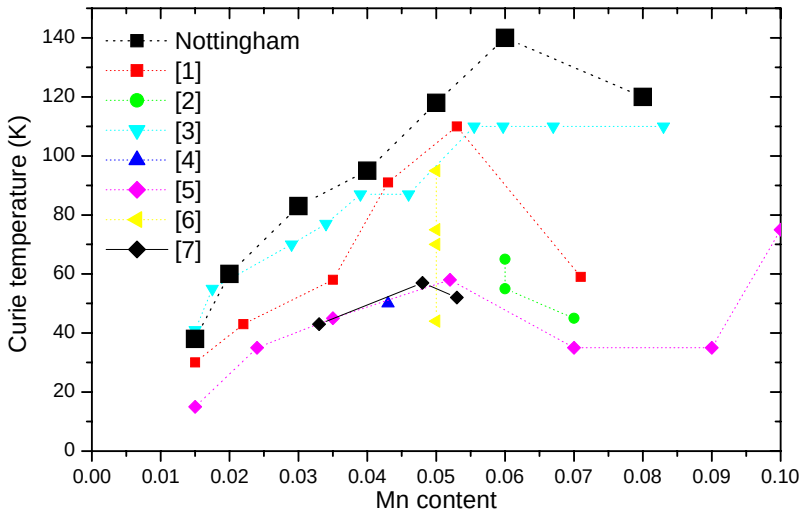
(Ga,Mn)As – Annealing Effect

Samarth-Schiffer Group – PSU – Unpublished





Curie temperature vs %Mn



[1] Ohno *et al*, PRB **57**, 2037 (1998) [2] Van Esch *et al*, PRB **56**, 13103 (1997)
[3] Potashnik *et al*, PRB **66**, 012408 (2002) [4] Shimizu *et al*, APL **74**, 398 (1999)
[5] Sadowski *et al*, APL **78**, 3271 (2001) [6] Hayashi *et al*, APL **78**, 1691 (2001)
[7] Baxter *et al*, PRB **65**, 212407 (2002)

Critical temperatures in excess of 150K have been achieved by several research groups, including Furdyna et al. at Notre Dame, Gallagher et al. at Nottingham and Samarth et al. at Penn State. Various strategies are being pursued in an effort to achieve even higher transition temperatures. Transition temperatures well in excess of room temperature will likely be required to make these materials technologically useful.

Summary of data from various groups assembled by Gallagher et al.

Theory

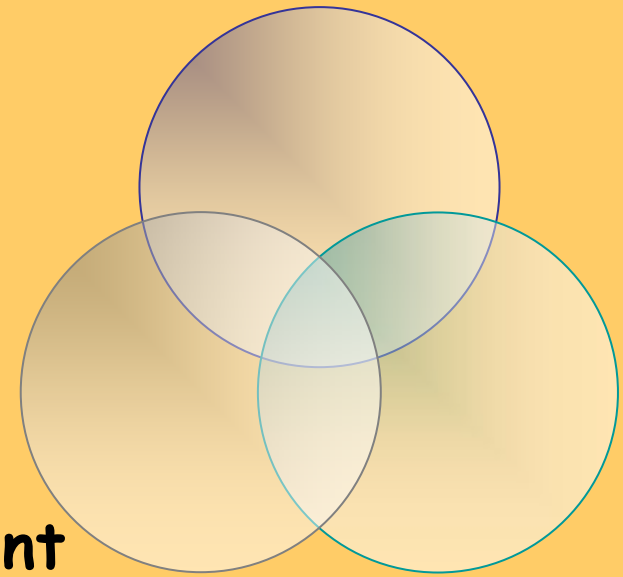
The magnetic, transport, and optical properties and their interrelationships are all of interest. The approach that I will discuss recognizes Mn moments and valence band holes as the low-energy degrees of freedom and includes a short-range exchange interaction between Mn local moments and valence band spins as the key interaction. Coulomb interactions between the Mn^{++} ions and holes are also important.

$$\sum_{I,\,j=v} J_{pd}\,\delta\left(\vec{r}_j - \vec{R}_I\right)\vec{s}_j \cdot \vec{S}_I$$

First principles LSDA approaches have also been used. These capture many qualitative aspects of ferromagnetism in these materials but do not represent the magnetic interactions accurately enough to address their details. On the other hand they are able to address larger energy scale physics, like that which controls the placement of Mn ions in the MBE growth process and to provide insight into the variation of properties across this class of materials.

Advantages of Models

Correct by Construction



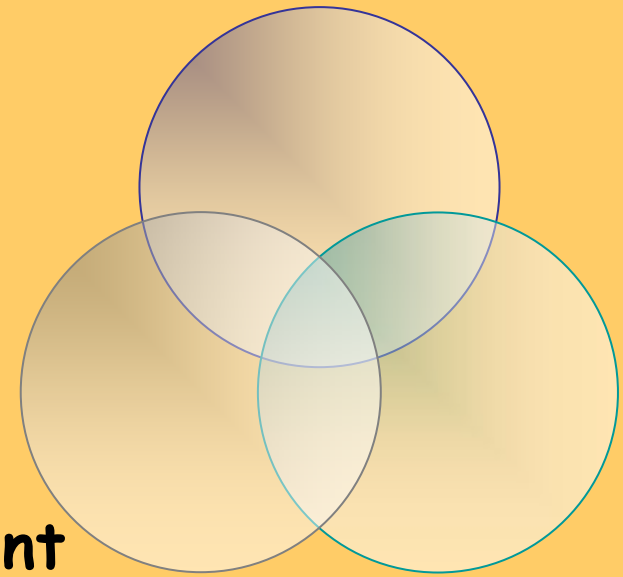
Transparent

Simpler

Disadvantage of Models

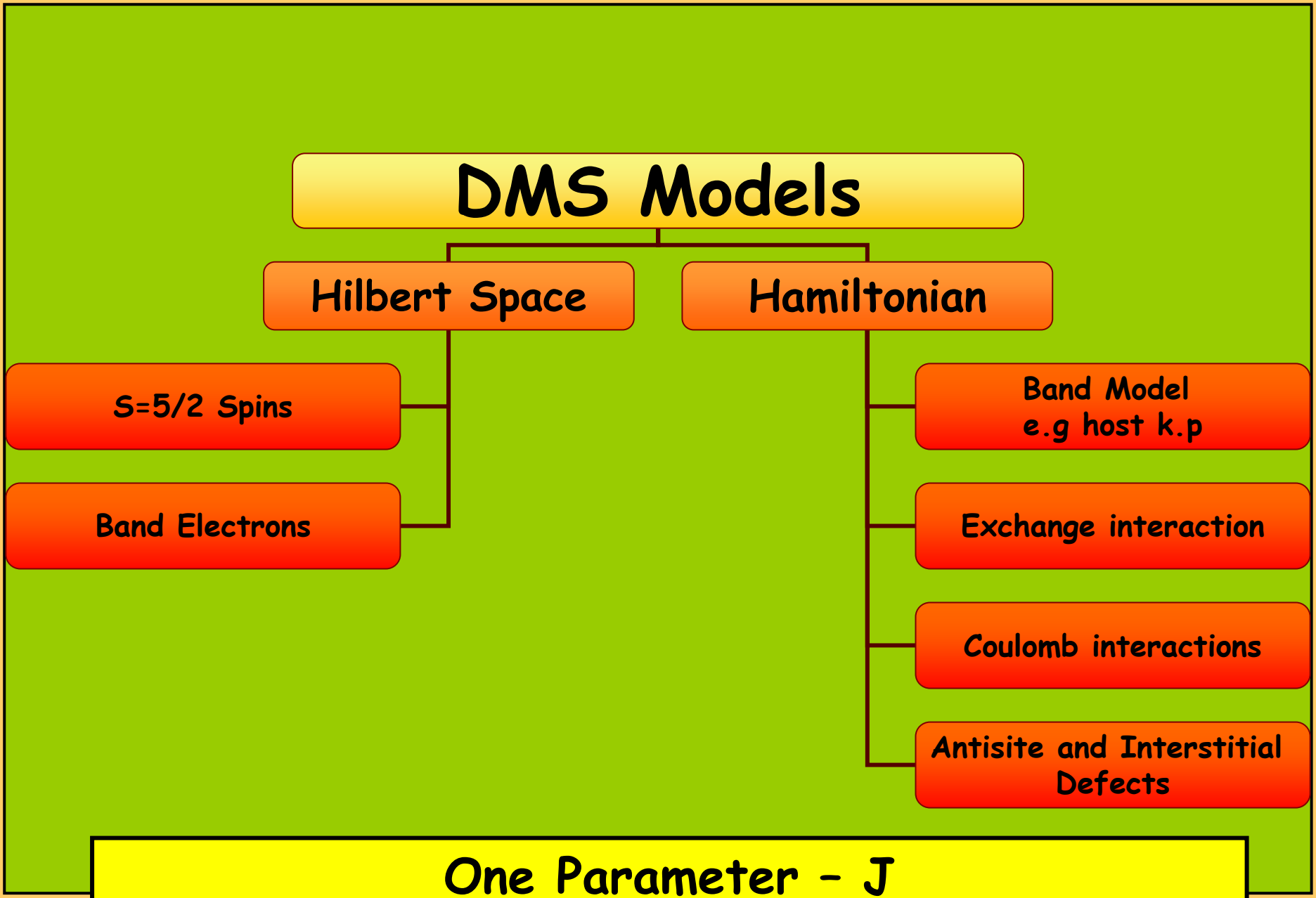
! Danger !

Can be Incorrect by Construction



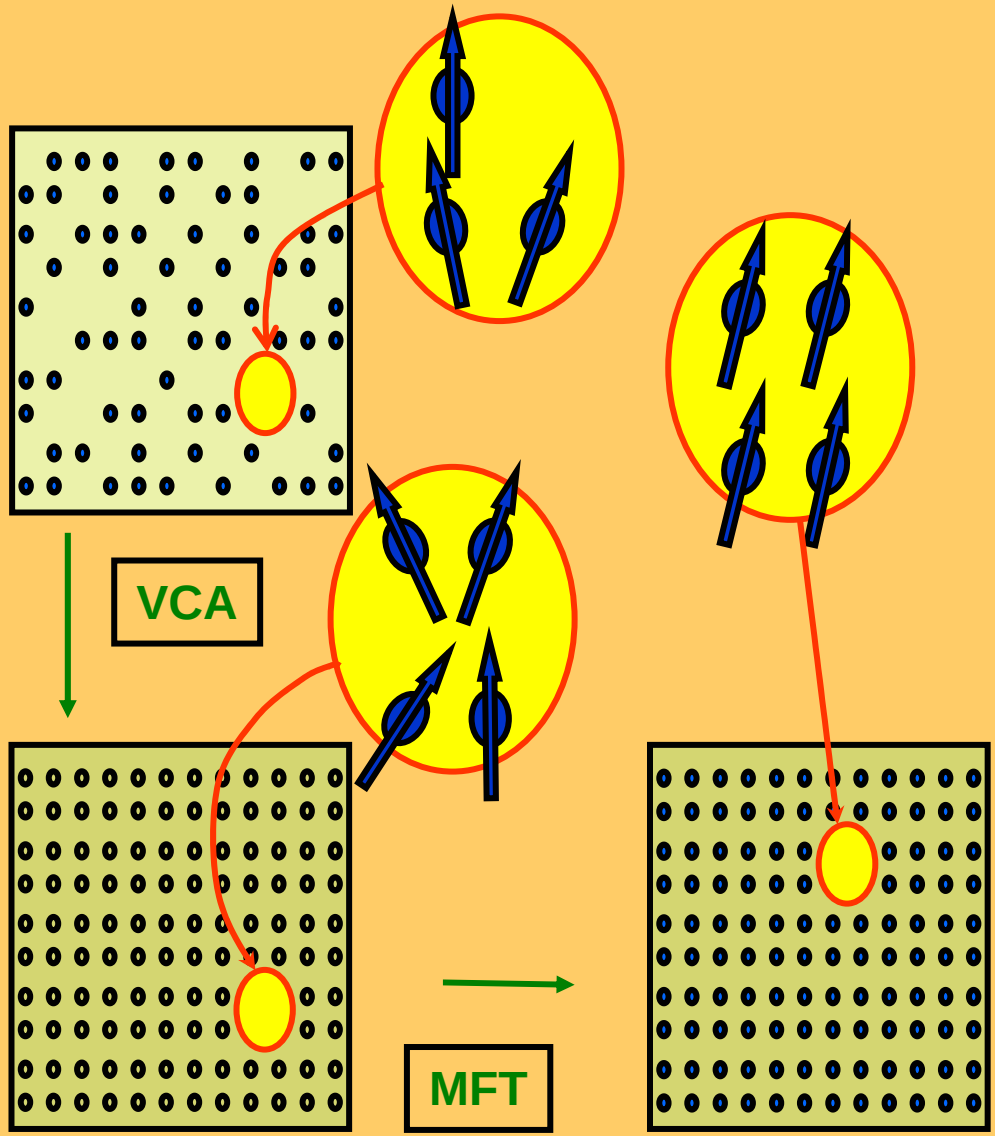
Transparent

Simpler



One Parameter – J
Uncontrolled (but possibly good) approximations

Virtual Crystal Approx & Mean-Field Theory



A lot of progress can be made by treating the disorder of these random alloys perturbatively and using a mean-field theory to describe their magnetic order.

Mean-Field Theory T_C

$$F(M,m) \sim T\,N_{[Mn]}\,M^2 + D^{-1}(\varepsilon_F)\,m^2 + J\,N\,S\,Mm$$

- **Stability of Paramagnetic State**

$$\frac{\partial^2 F}{\partial m^2} \bullet \frac{\partial^2 F}{\partial M^2} \geq \left(\frac{\partial^2 F}{\partial M \partial m}\right)^2$$

$$\Rightarrow T_C \sim J^2 N\,D(\varepsilon_F)$$

Mean-field theory considers only uncorrelated variation in the average local moment polarization (M) and the average band spin-density. Isolated local moments have a purely entropic free energy that favors an unpolarized configuration. Band spin-polarization has an energy cost inversely proportional to the density of states. Because the local moment stiffness is purely entropic the total free energy including the interaction term always favors ferromagnetism (m,M not zero) at sufficiently low T

Mean-Field Theory Successes

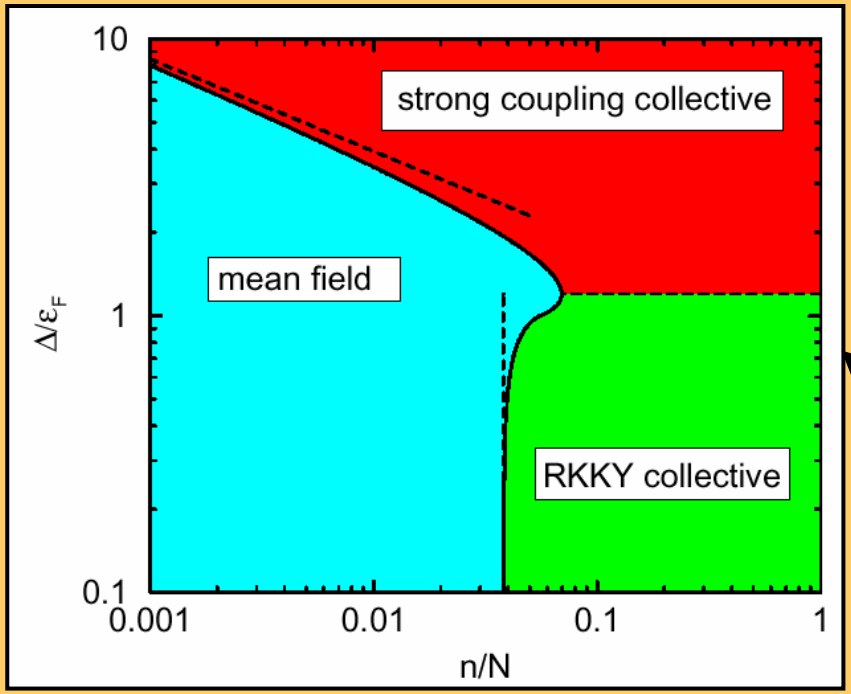
Magnetic Properties:
T_c, K(T,e), A(T,e)
Domains, FMR …

Optical Properties:
IR $\sigma(w)$, MCD,…

Transport Properties
AMR, AHE, σ

Curie Temperature

Mean-field theory is expected to fail for large band density of states and for high carrier density. Realistic features of the band structure are critical in assessing whether or not corrections to mean-field theory are important. In particular complex Fermi surfaces help to reduce the importance of oscillatory coupling between moments at high carrier densities. The high density-of-states heavy-hole bands are necessary to get local magnetic order at high T. The low denisty-of-states light-hole bands provide most of the magnetic stiffness that help to supress thermal fluctuations and make mean-field-theory T_c estimates reasonable accurate.

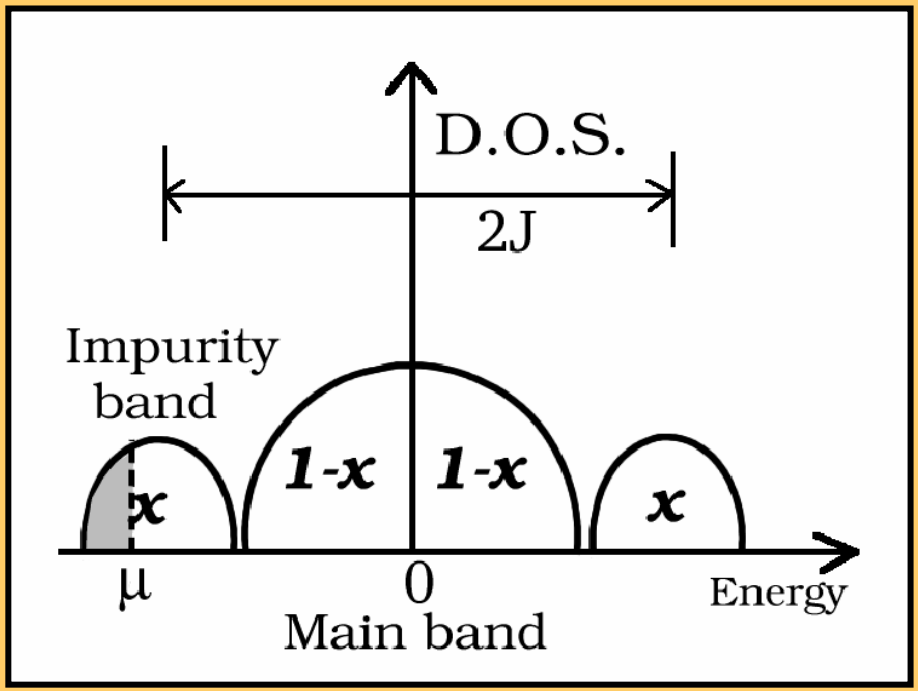


Schliemann APL 78, 1550 (2001)

Key Issue within Model Approach

When is there an impurity band?

Realistic band models are also necessary to estimate the Mn fraction to which well defined impurity bands associated with Mn acceptor levels survive.



Alvarez and Dagotto cond-mat/0303

compare Yang+AHM PRB (2003)

Shallow Acceptor

110 meV ~ 40+40+30

Cutoffs Important

ANOMALOUS HALL EFFECT

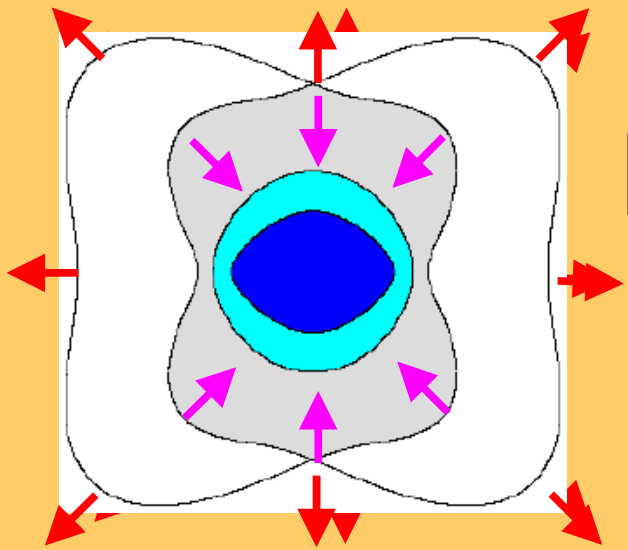
k-space Berry curvature

$$\sigma_{AH} = -\frac{e^2}{\hbar}\sum_n \int \frac{d\vec{k}}{(2\pi)^3} f_{n,\vec{k}} \Omega_z(n,\vec{k}) ,$$

$$\Omega_z = 2\mathrm{Im}[\langle \frac{\partial u}{\partial k_y} | \frac{\partial u}{\partial k_x} \rangle].$$

These ferromagnets have a very large anomalous Hall effect because of strong spin-orbit coupling in the valence band. We have explained the AHE in terms of the heavy-hole wavefunctions, which are (nearly) spin-coherent states, as an intrinsic effect. The same theory explains the AHE in transition metals, a mystery of long standing

Jungwirth et al. PRL 2002



$$H_0 = \frac{\hbar^2}{2m}\left[(\gamma_1 + \frac{5}{2}\gamma_2)k^2 - 2\gamma_2(\boldsymbol{k}\cdot\boldsymbol{j})^2\right]$$

Optical Spin Transfer

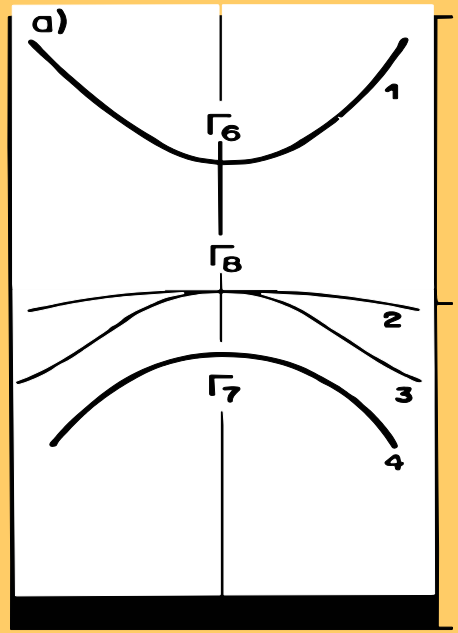
One of the potentially interesting aspects of ferromagnetic semiconductors is their interaction with light. Because of spin-orbit coupling, it is possible to create spin-polarized carriers in semiconductors with light – this effect is called optical orientation and has been known for many years. In ferromagnetic semiconductors, spin-polarized light drives the quasiparticles from equilibrium and can influence the collective magnetization.

Optical Orientation

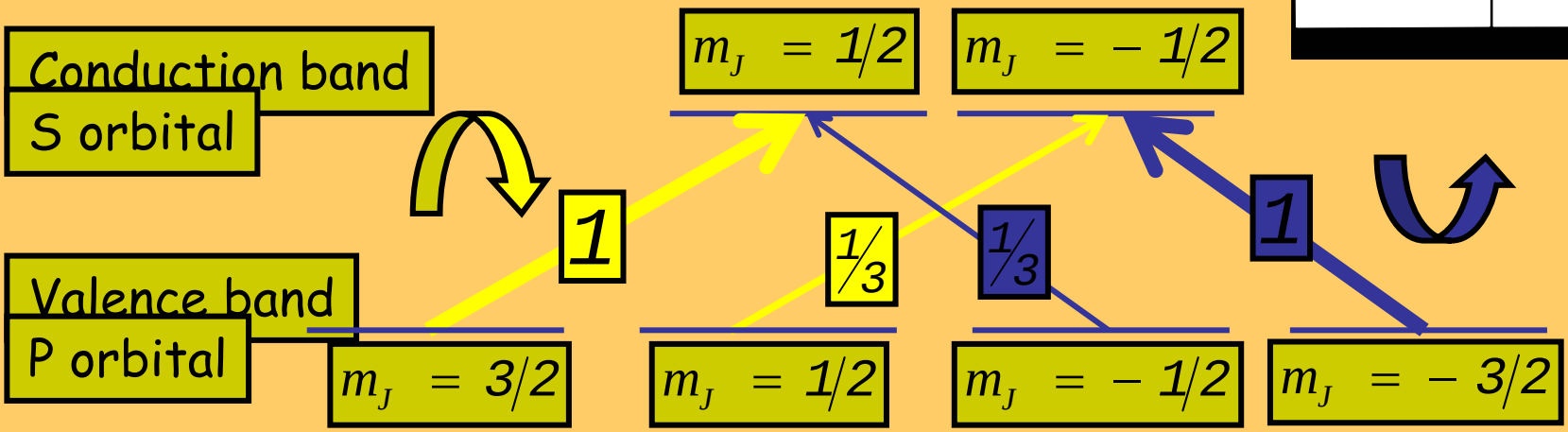
Light induced carriers **e-h pairs**

Circularly polarized light

$$\Delta J = 1$$
$$\Delta m = \pm 1$$



Because the states at the top of the valence band are L=1,J=3/2, spin-orbit coupled levels, polarized light can be used to creat spin-polarized electrons and holes.

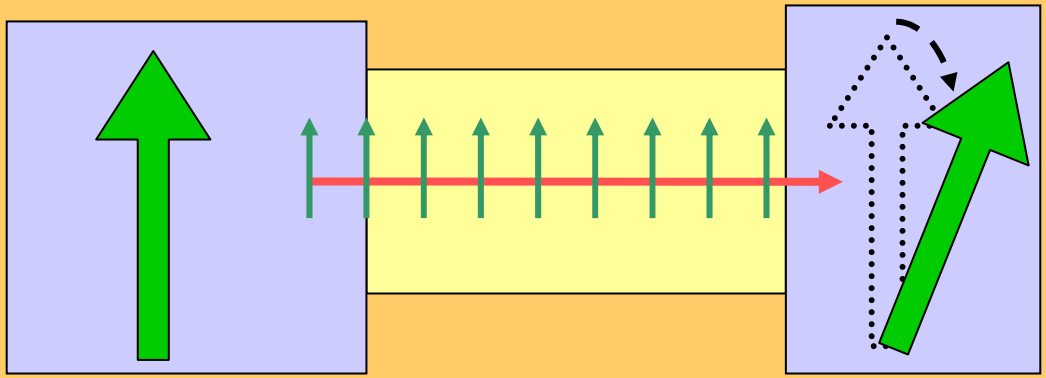


Holes: Strong spin orbit interaction

L. L. Slonczewski Equation

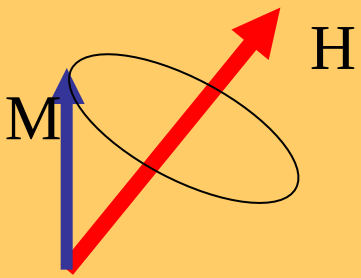
CURRENT DRIVEN MAGNETIZATION SWITCHING

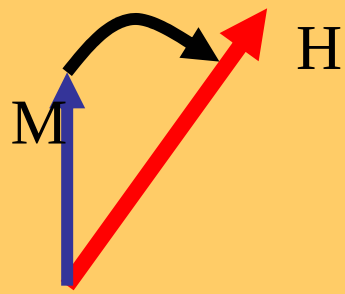
Ferromagnetic particle



Ferromagnetic particle

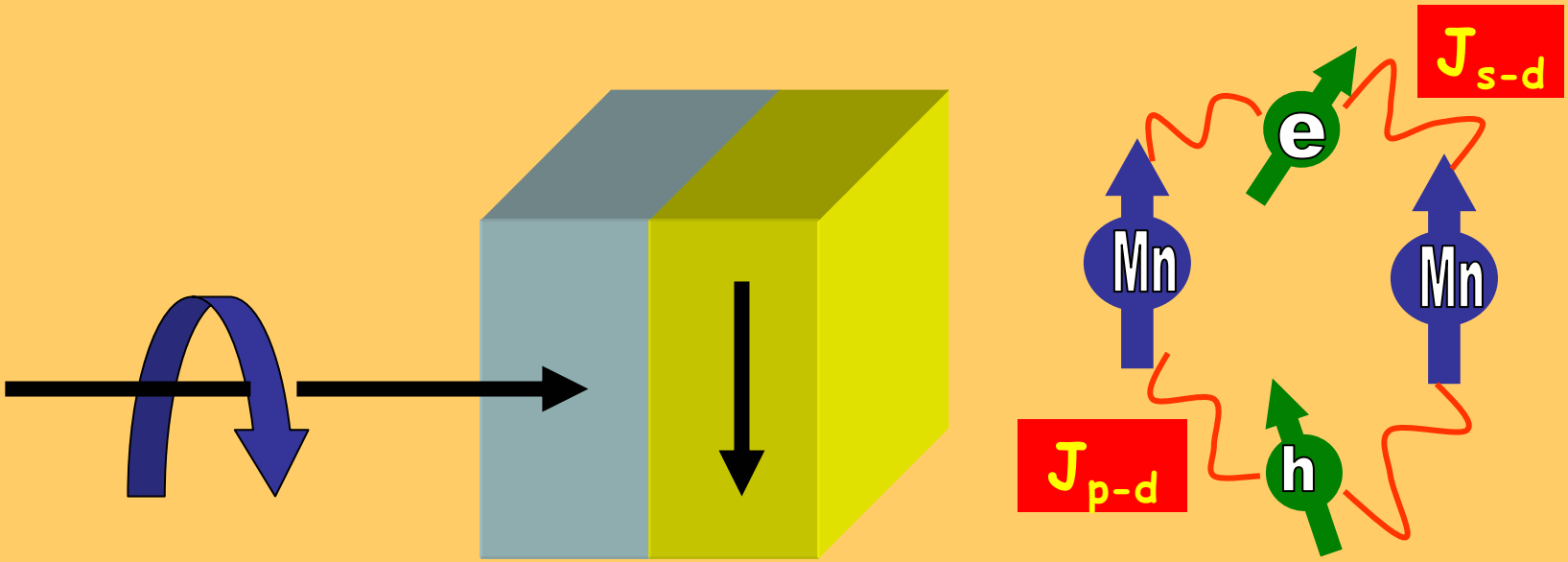
$$\frac{d\vec{M}}{dt} = -\gamma \vec{M} \times \vec{H} + \frac{\gamma\alpha}{M} \vec{M} \times (\vec{M} \times \vec{H}) + \vec{\Gamma}$$





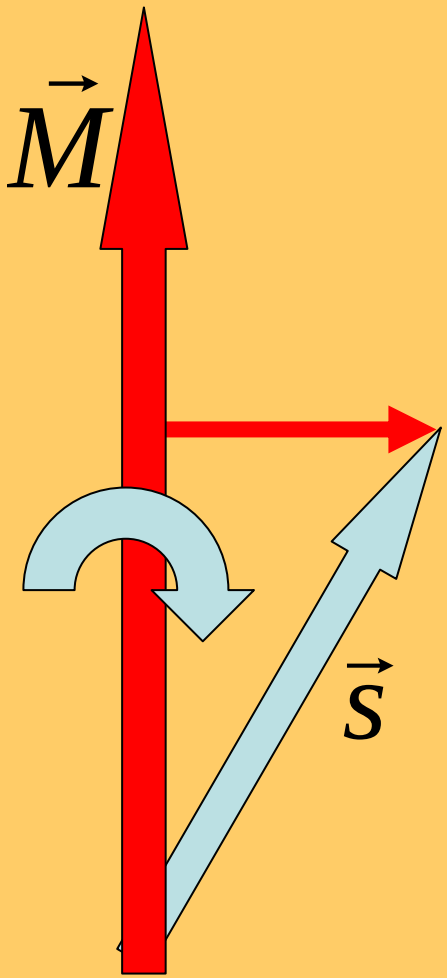
Spin Torque

Optical Spin Transfer in (Ga:Mn)As



Álvaro S Núñez
Joaquín Fernández-Rossier, Ramin Abolfath

Optical Slonzcewski Torque Qualitative Picture

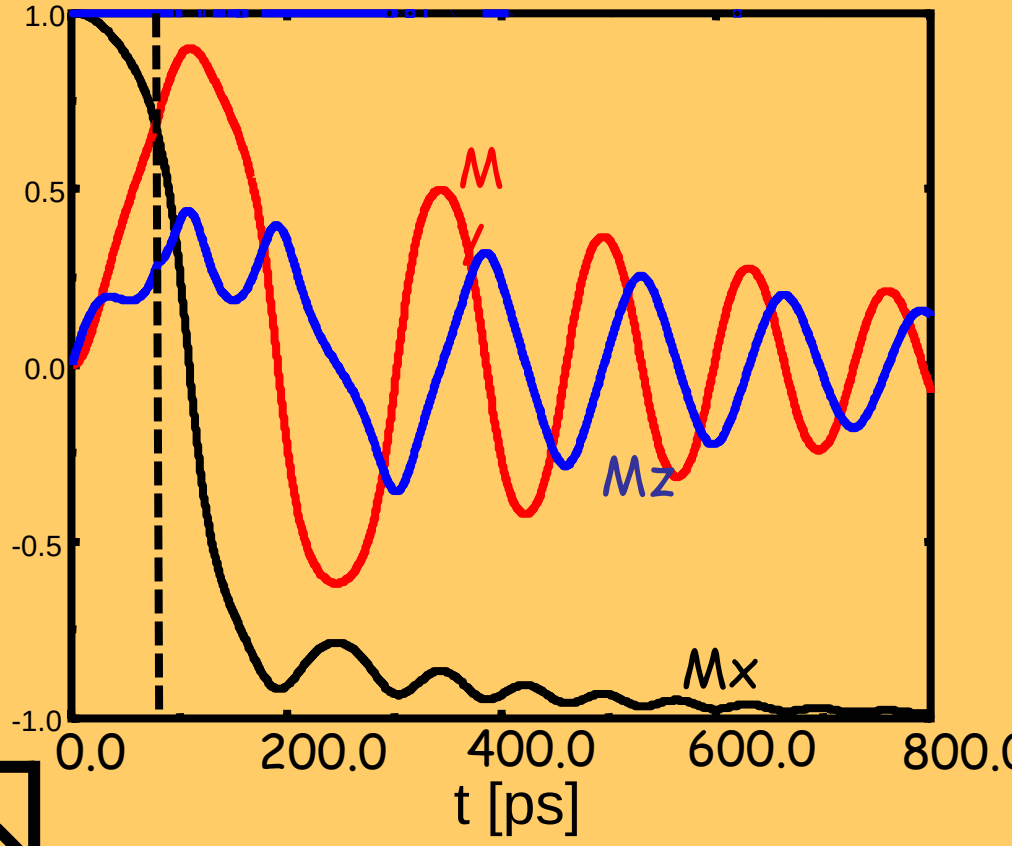


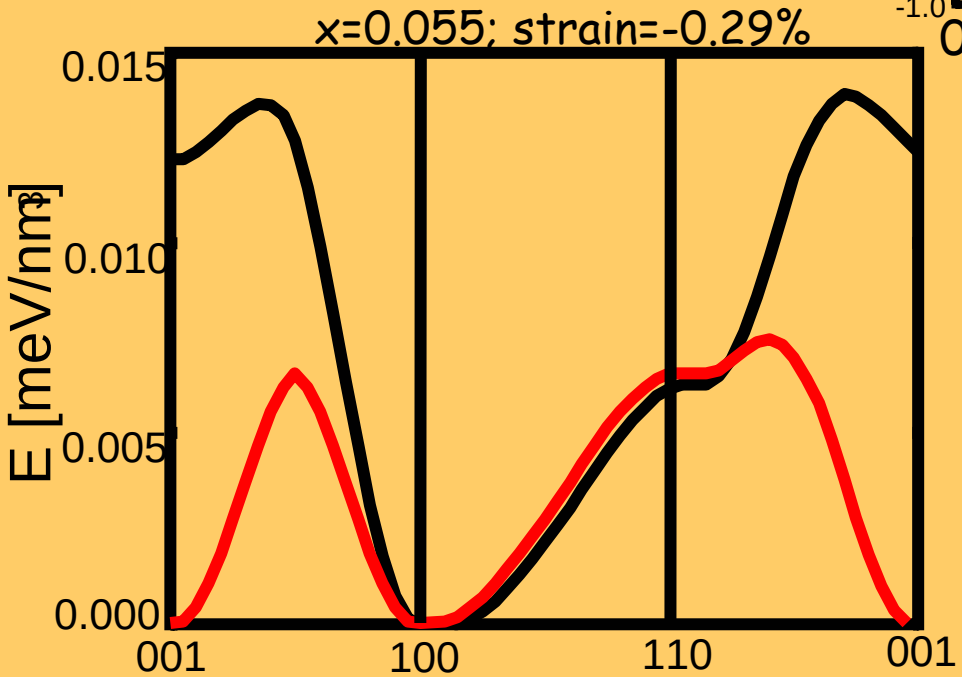
$$\vec{\Gamma} = gP\vec{M} \times (\vec{s} \times \vec{M})$$

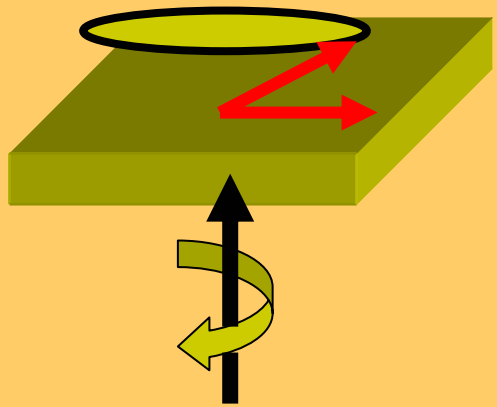
Optical Spin Transfer

$Laser\_Pulse = 6.0 MW / cm^2$

$\alpha = 0.04$







(III,Mn)V Ferromagnetism

- We're making progress
- Spin-orbit coupling essential and interesting
- Compensating defects essential

Useful for semiconductor spintronics?