Colloquium@NTHU
Sep 22, 2004

Spintronics at Nanoscale

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Nat'l Tsing-Hua Univ & Nat'l Center for Theoretical Sciences

What I have been doing…

Spintronics:

- Green's function theory for diluted magnetic semiconductor at finite temperature, Phys. Lett. A (2004).
- Spiral exchange across DMS junction, Appl. Phys. Lett. (2004).
- Spintronics at nanoscale -- flat-band ferromagnetism in armchair nanoribbons and nanotubes.

Low-D Correlated Systems:

- Renormalization-group potential in quasi-1D correlated systems, Phys. Rev. B (2004).
- Phonons in Hubbard ladders, cond-mat/0408665.
- Electron fractionalization in N-leg ladders (Not yet finished).

Edge Physics:

- Andreev edge state in Na_xCoO_2, cond-mat/0407187.
- Ground-state degeneracy of an insulator with edges.
- Magnetic carbon STM tip (Not yet finished).

Collaborators

Spin-Wave Theory

for Diluted Magnetic Semiconductor

- Jurgen Konig
- John Schliemann
- Allan MacDonald

-- Phys. Rev. Lett. ***84****, 5628 (2000)*
-- Appl. Phys. Lett. ***78****, 1550 (2001)*
-- Springer's Lecture Notes in Physics ***579***

Green's Function Approach

for Diluted Magnetic Semiconductor

- Shih-Jey Sun
- Song-Shien Chen

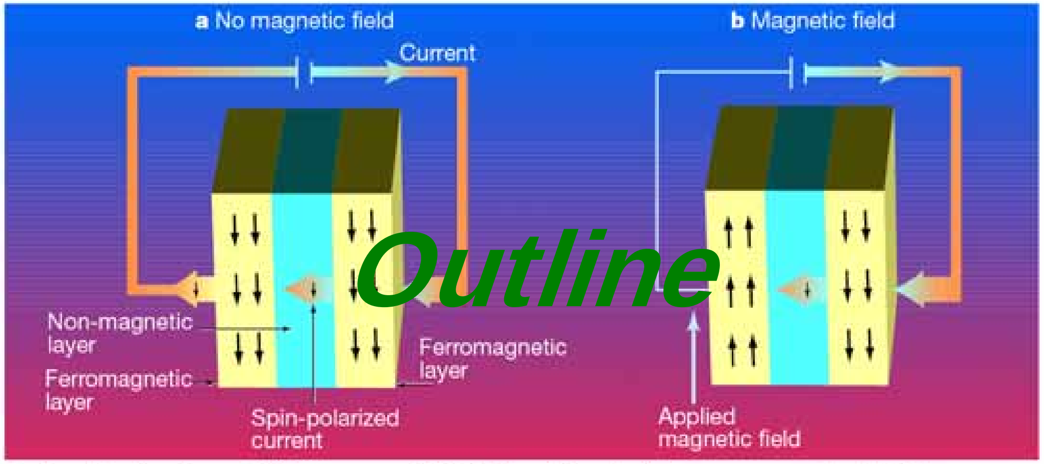
-- Phys. Rev. Lett. ***86****, 5637 (2001)*
-- Appl. Phys. Lett. ***84****, 2862 (2004)*
-- Phys. Lett. ***A 327****, 73 (2004)*

Spintronics at Nanoscale

- Toshiya Hikihara
- Xiao Hu
- Chung-Yu Mou
- Bor-Lung Huang

-- Preprint available upon request :)

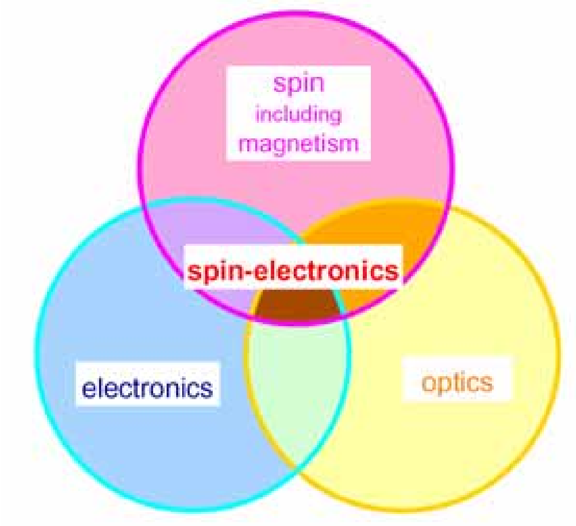
Outline



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.

- *Introduction to Spintronics*
- *Diluted Magnetic Semiconductor*
- *DMS Junctions at Nanoscale*
- *Ferromagnetism in Nanoribbon/Nanotube*
- *Remarks*

What is "spintronics" ?



Spintronics is a multidisciplinary field including magnetism, semiconductor physics, optics, mesoscopic physics, superconductivity and new connections to other fields.

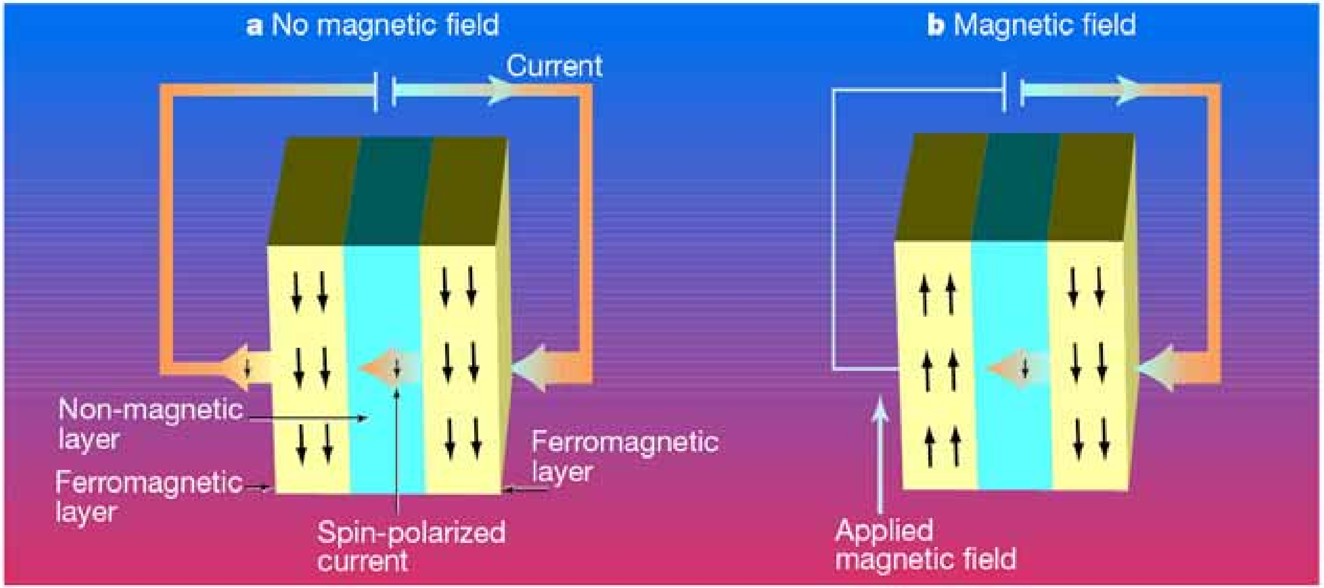
Spintronics* = *Spin* + *Electronics

The central theme is how to manipulate the spin degrees of freedom which interact with the solid-state environment.

Spin-Dependent Transport

Conventional transistors make use of current or voltage to control the transmitted current -- ***electronics.***

Nature 404, 918 (2000)



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.**

Use spin configurations to control the current

-- spintronics !

CMR v.s. TMR

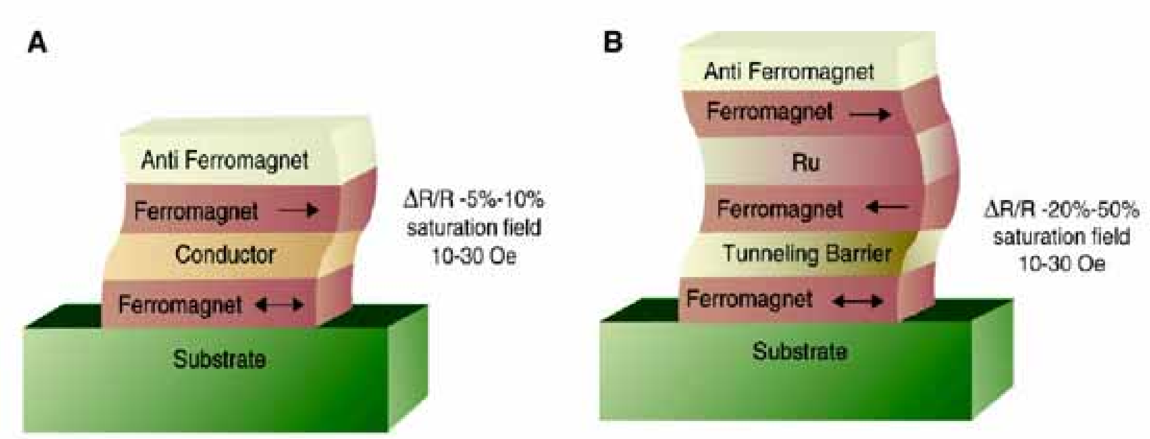


Fig. 1. Spin-dependent transport structures. (**A**) Spin valve. (**B**) Magnetic tunnel junction.

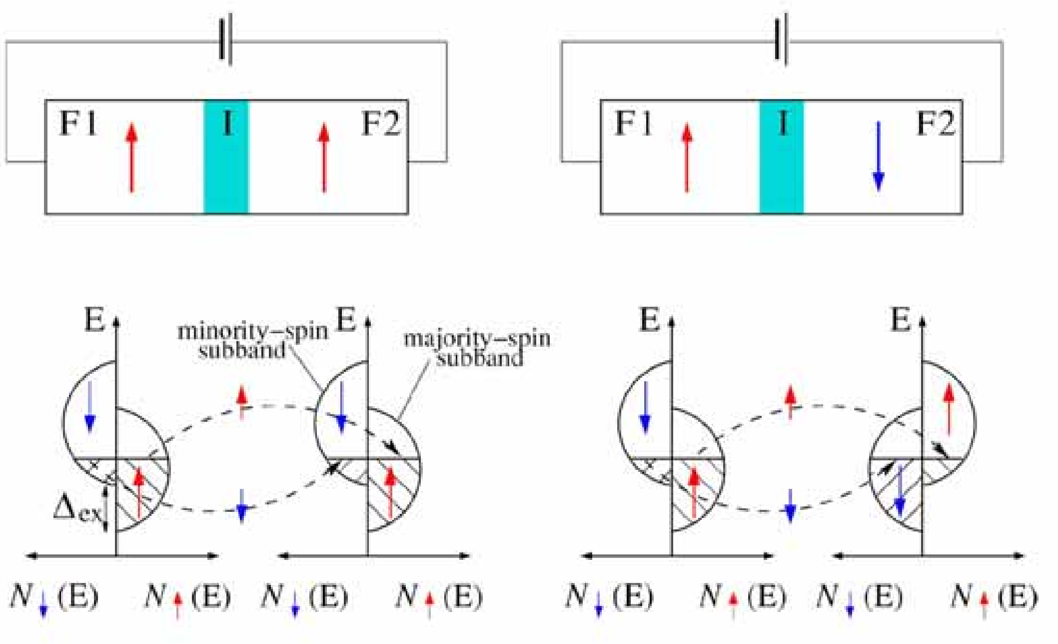
The most commonly built structures for spin-dependent transport make use of

(a) Giant Magnetoresistance effect (GMR)

(b) Tunneling Magnetoresistance effect (TMR)

Tunneling Magnetoresistance (TMR)

Tunneling conductance across the barrier is proportional to the product of density of states on both sides, $G \sim N_R N_L$.



$G_{\uparrow\uparrow} \sim \mathcal{N}_{M1}\mathcal{N}_{M2} + \mathcal{N}_{m1}\mathcal{N}_{m2}$ $\quad G_{\uparrow\downarrow} \sim \mathcal{N}_{M1}\mathcal{N}_{m2} + \mathcal{N}_{m1}\mathcal{N}_{M2}$

Julliere model for TMR

Tunneling magnetoresistance (TMR) is defined as the ratio of resistance change and the low resistance:

Spin Polarization is defined as:

$$P = \frac{\mathcal{N}_M - \mathcal{N}_m}{\mathcal{N}_M + \mathcal{N}_m}$$

$$TMR \equiv \frac{\Delta R}{R_{\uparrow\uparrow}} = \frac{R_{\uparrow\downarrow} - R_{\uparrow\uparrow}}{R_{\uparrow\uparrow}} = \frac{G_{\uparrow\uparrow} - G_{\uparrow\downarrow}}{G_{\uparrow\downarrow}}$$

In the tunneling limit, the conductance is proportional to the ***product of densities of states*** on both sides of the junction.

$$TMR = \frac{2P_1P_2}{1 - P_1P_2}$$

Datta-Das Spin Field-Effect Transistor

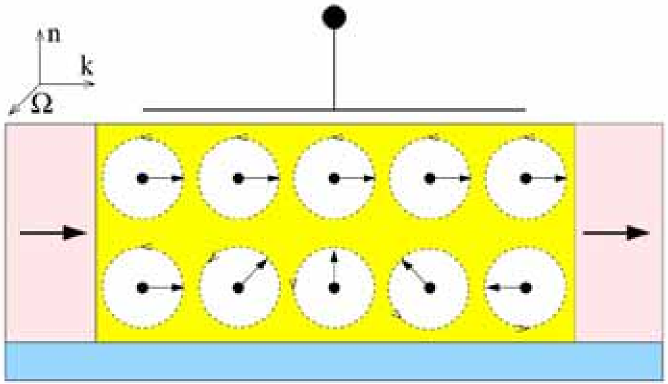


FIG. 1. (Color in online edition) Scheme of the Datta-Das spin field-effect transistor (SFET). The source (spin injector) and the drain (spin detector) are ferromagnetic metals or semiconductors, with parallel magnetic moments. The injected spin-polarized electrons with wave vector **k** move ballistically along a quasi-one-dimensional channel formed by, for example, an InGaAs/InAlAs heterojunction in a plane normal to **n**. Electron spins precess about the precession vector $\mathbf{\Omega}$, which arises from spin-orbit coupling and which is defined by the structure and the materials properties of the channel. The magnitude of $\mathbf{\Omega}$ is tunable by the gate voltage V_G at the top of the channel. The current is large if the electron spin at the drain points in the initial direction (top row)—for example, if the precession period is much larger than the time of flight—and small if the direction is reversed (bottom).

-- Datta and Das,
Appl. Phys. Lett. **56**, 665 (1990)

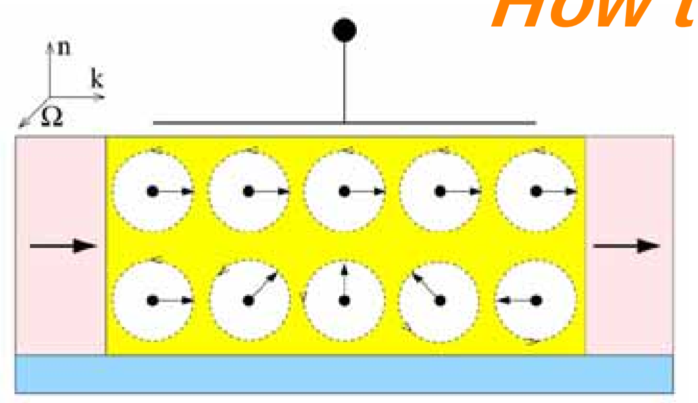
-- Zutic, Fabian and Das Sarma,
Rev. Mod. Phys. **76**, 323 (2004)

Key Issues

-- Datta and Das,
Appl. Phys. Lett. **56**, 665 (1990)

-- Zutic, Fabian and Das Sarma,
Rev. Mod. Phys. **76**, 323 (2004)

How to polarize spins?



How to detect spins?

How to maintain spin coherence?

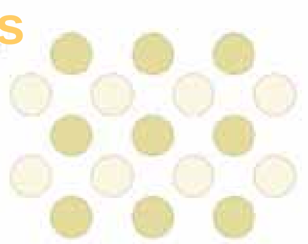
Charge and Spin

Charge: data processing
by semiconducting materials

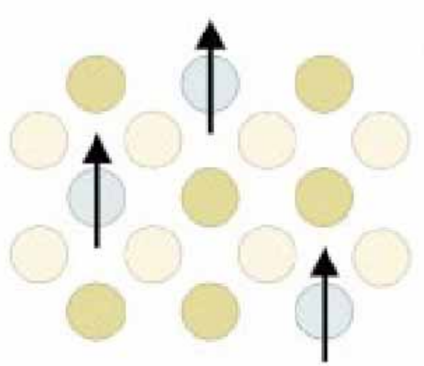
Spin: memory storage
by magnetic materials

Diluted Magnetic Semiconductor

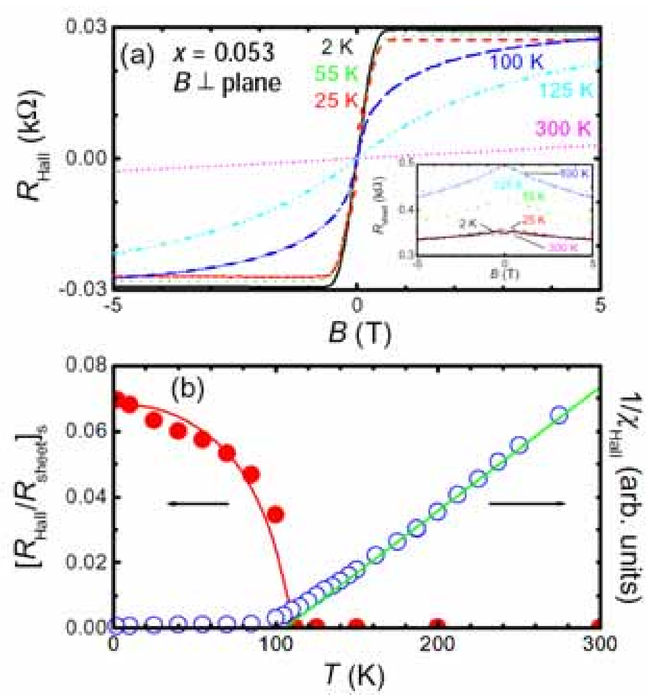
Ga As



(Ga, Mn) As



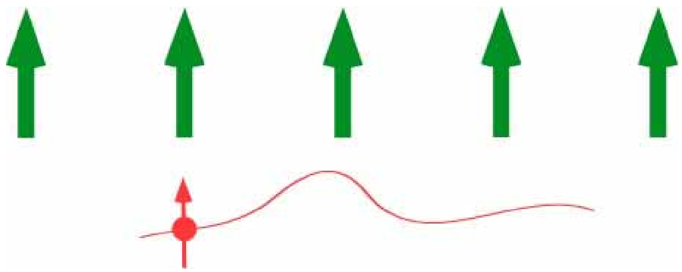
(Ga,Mn)As becomes ferromagnetic below Curie temperature T_c.



Right now, record high is around 160 K, by Edmonds *et al.*, Phys.Rev. Lett. 92, 037201 (2004).

Origin of Ferromagnetism?

Dietl *et al.*,
Science **287**, 1019 (2000)

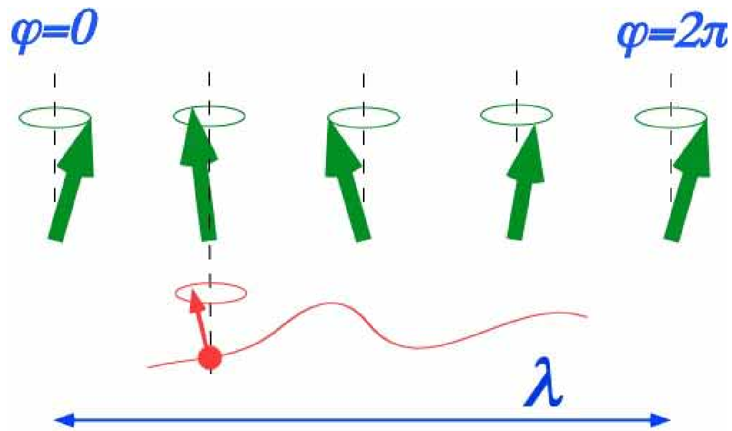


Double Exchange -- itinerant carriers align Mn spins, generating effective ferromagnetic exchange coupling among local moments.

Zener model -> minimize the free energy from kinetic and exchange parts <u>without</u> spatial fluctuations

Spin-wave theory -> minimize the free energy from kinetic and exchange energies without spatial fluctuations

Konig, Lin, MacDonald
Phys. Rev. Lett. **84**, 5628 (2000)

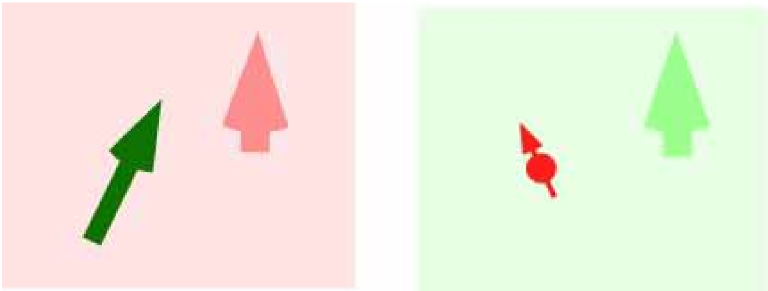


Mean-Field Prediction

The polarization can be evaluated in mean-field limit by replacing all other spins with an effective magnetic field.

$$\langle S_z \rangle = \chi_C \, H = \frac{S(S+1)}{3kT} \; g\mu_B H$$

$$\langle s_z \rangle = \chi_P \, h = \left(\frac{\chi_P}{g^* \mu_B} \right) \; g^* \mu_B h$$



The spin polarizations of Mn ions and itinerant holes under external magnetic field are described by **Curie** and **Pauli** susceptibilities.

Self-consistent equations at $T = T_c$

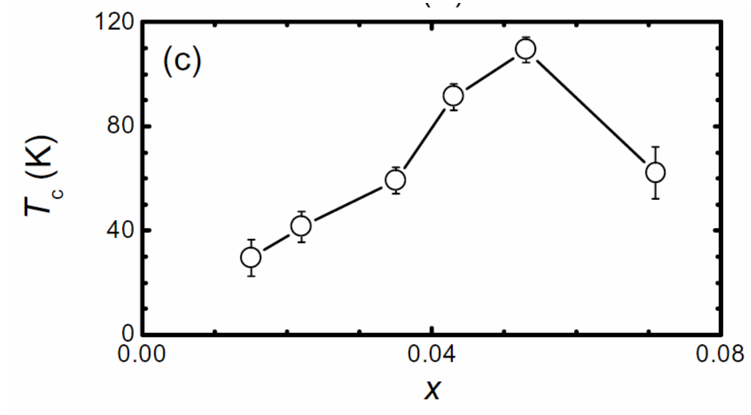
$$\langle S_z \rangle = \frac{S(S+1)}{3kT_c} \; J \, n_e \langle s_z \rangle$$

$$\langle s_z \rangle = \left(\frac{\chi_P}{g^* \mu_B} \right) \; J \, n_{Mn} \langle S_z \rangle$$

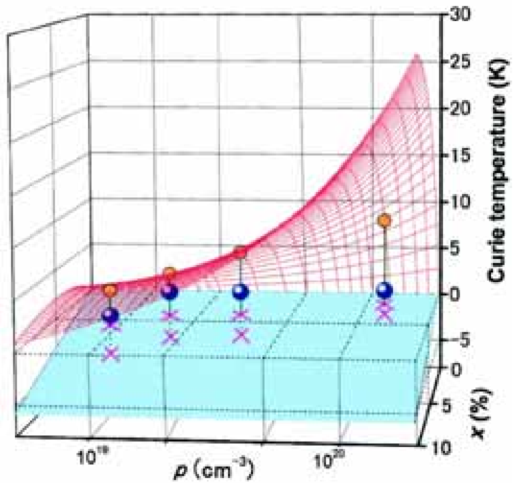
$$kT_c = \frac{S(S+1)}{3} \left(\frac{\chi_P}{g^* \mu_B} \right) J^2 \; n_{Mn}$$

Curie Temperature

Exp Data for (Ga, Mn) As:



Theory for (Ga, Mn) As:



Dietl *et al.*,
Science **287**, 1019 (2000)

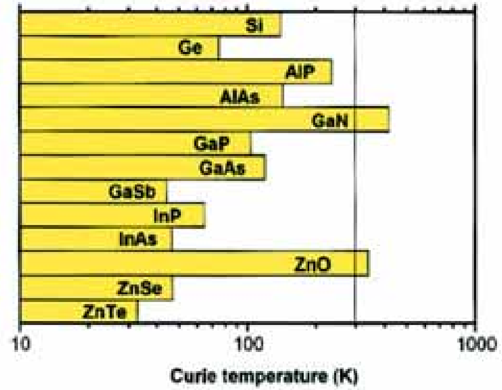
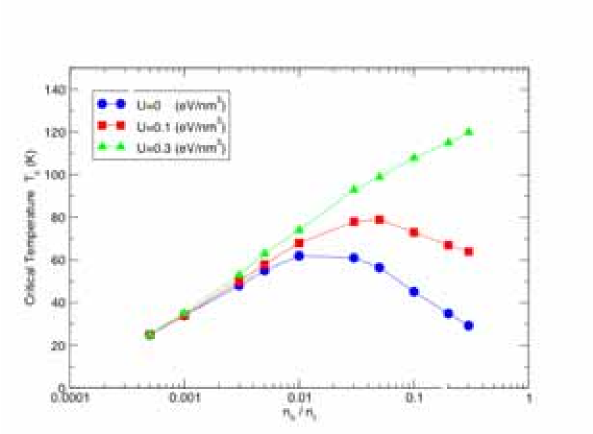


Fig. 3. Computed values of the Curie temperature T_C for various p-type semiconductors containing 5% of Mn and 3.5×10^{20} holes per cm^3.

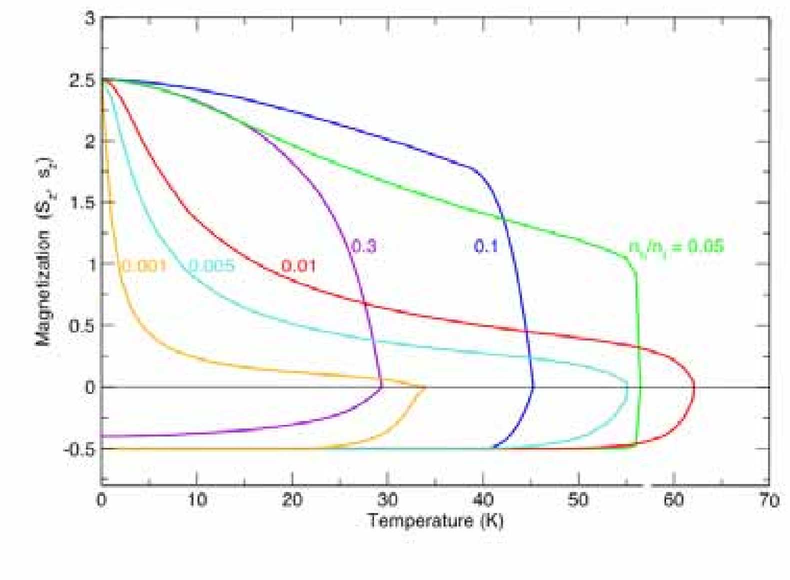
Theoretical prediction for room temperature DMS?!

For discussions, see **Saito *et al.*, Phys. Rev. Lett. 90, 207202 (2003)**

DMS at Finite Temperature



Sun and Lin,
Phys. Lett. A **327**, 73 (2004)



Green's function approach provides a self-consistent description for thermal fluctuations at finite temperature. It can be viewed as the combination of Zener model and spin-wave theory.

This formulism also opens up a new perspective to look into the spin-wave excitations. It provides the chance to investigate whether spin waves remain "sharp" in the sense of quantum particles.

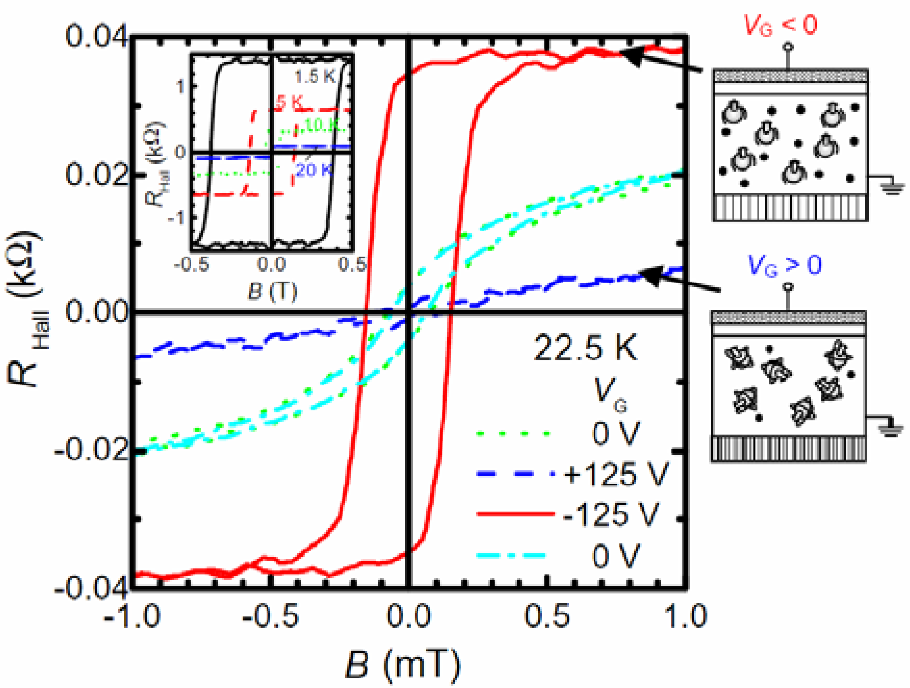
Field Effect in DMS

Since the feromagnetism is mediated by the itinerant carriers. One expects the magnetic properties are ***sensitive to carrier concentration***.

Ohno *et al.*,
Nature **408**, 944 (2000)

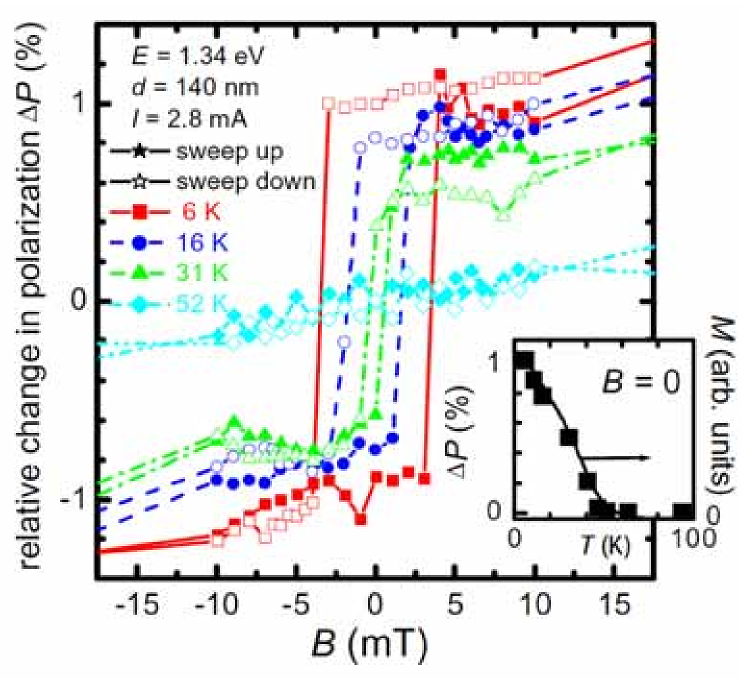
By varying the ***gate voltage***, one can manipulate the concentration of itinerant carriers.

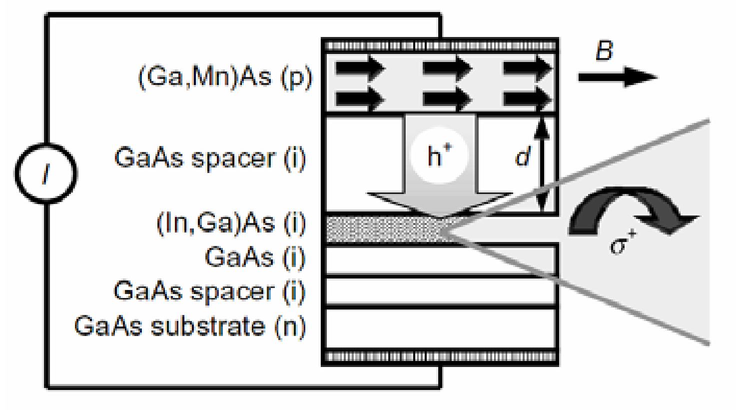
It is rather remarkable that the magnetic property can be controlled by the gate voltage easily!



Spin Injection

Ohno *et al.*,
Nature **402**, 790 (1999)

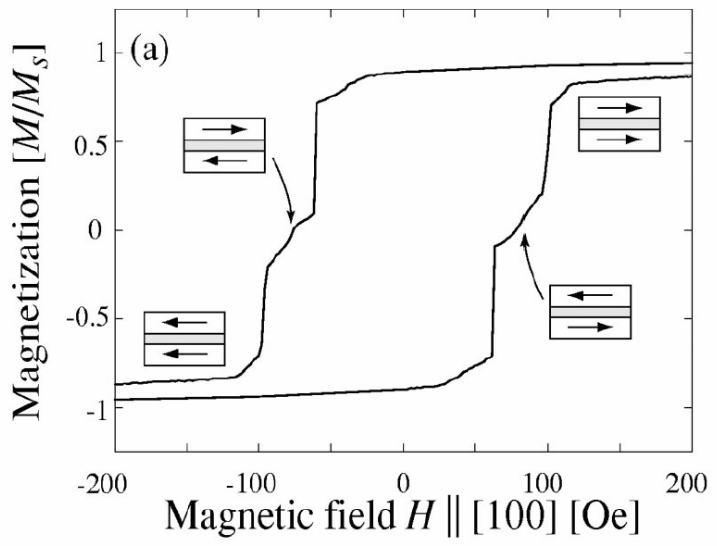


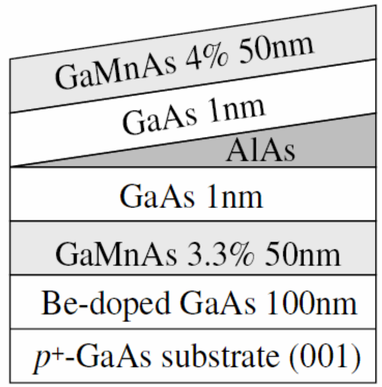


Polarized holes recombined with electrons, creating circularly polarized light by angular momentum transfer.

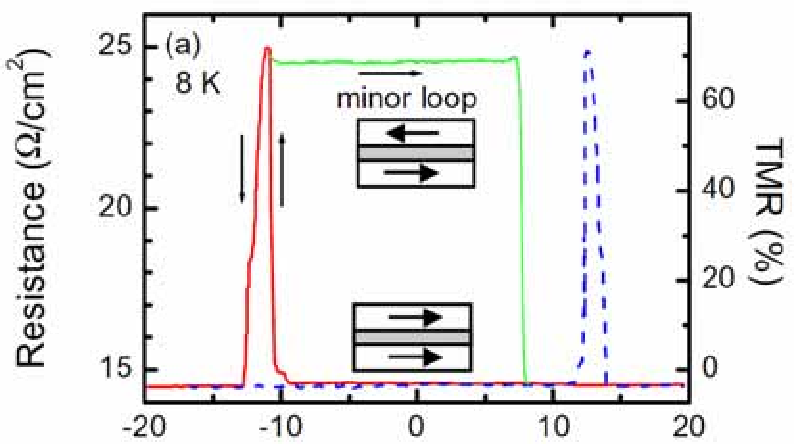
By measuring the intensity of the polarized light emission, we can estimate the efficiency of ***spin injection*** in the all-semiconductor setup.

TMR Junction





Tanaka and Higo,
Phys. Rev. Lett. **87**, 026602 (2001)



Large TMR (about 70% at 8 K) is achieved in epitaxially grown (Ga, Mn)As/AlAs/(Ga,Mn)As junction.

RKKY Interaction

Parkin and Mauri,
Phys. Rev. B **44**, 7131 (1991)

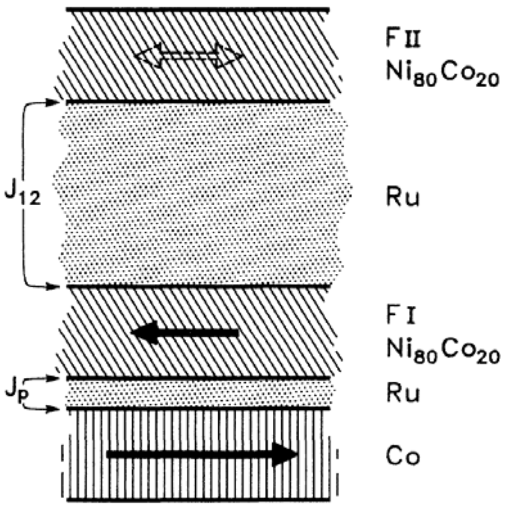
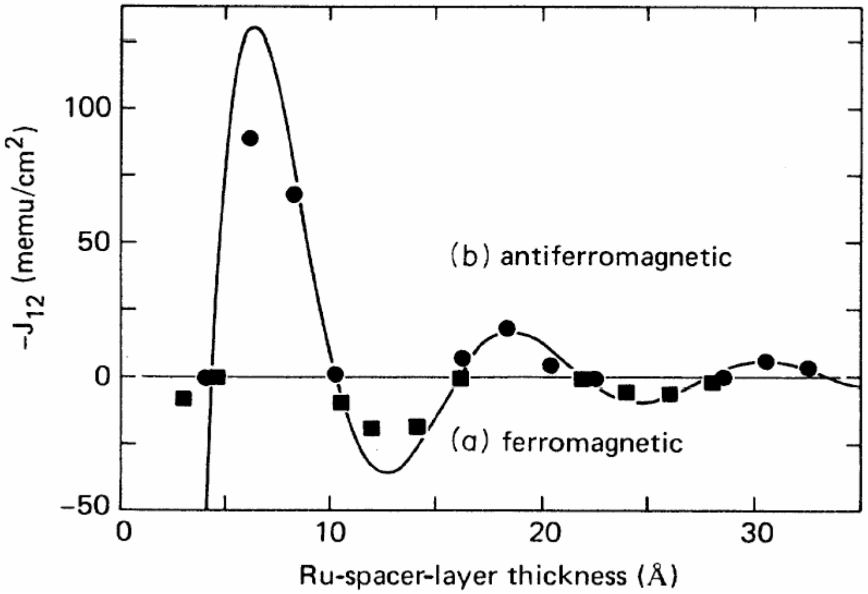


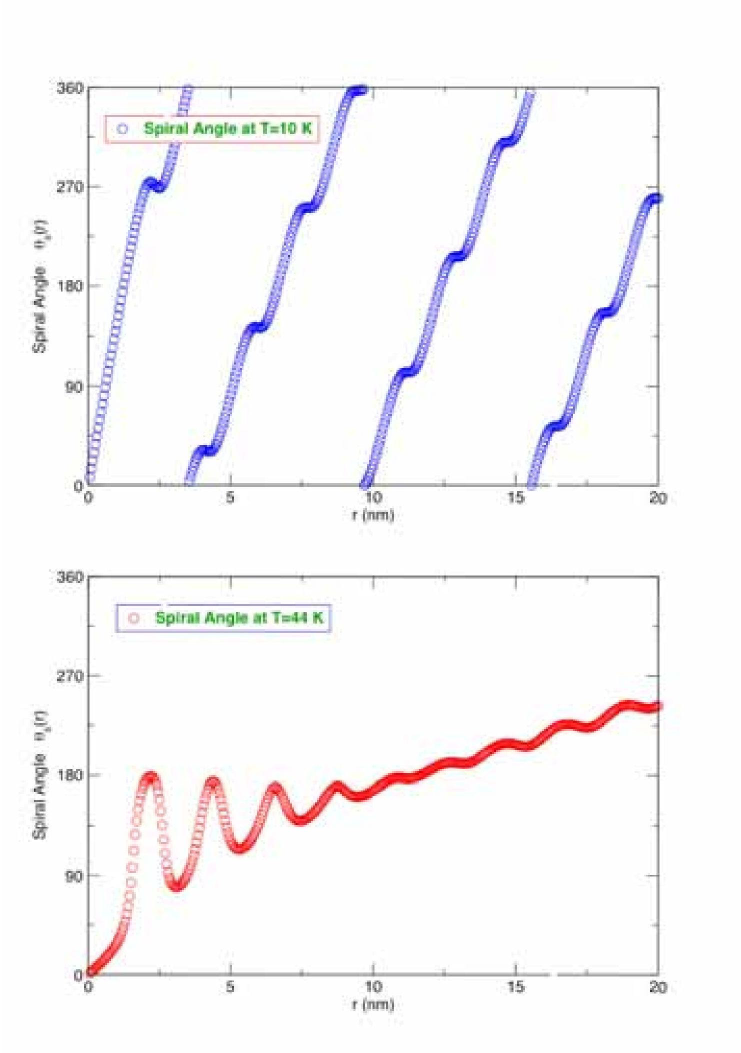
FIG. 1. Schematic diagram of sample structure. The exchange coupling, J_{12}, between two $Ni_{80}Co_{20}$ layers is measured by pinning the moment of one of the $Ni_{80}Co_{20}$ layers (F I) antiparallel to a Co layer. The moment of the Co layer is set equal to the sum of the moments of the two $Ni_{80}Co_{20}$ layers.

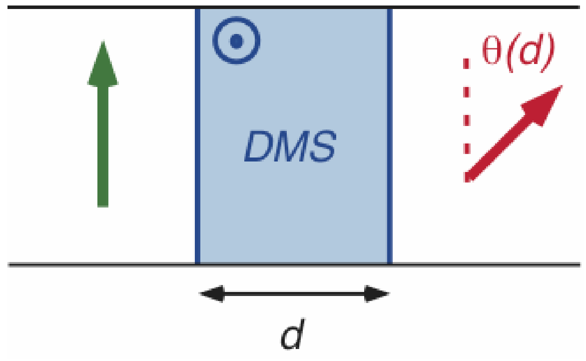


The exchange coupling mediated by itineant carriers in the metal layer is either ferromagnetic (F) or antiferromagentic (AF) ***depending on the thickness of the metal layer***.

Spiral Exchange

Sun, Chen, Lin,
Appl. Phys. Lett. **84**, 2862 (2004)



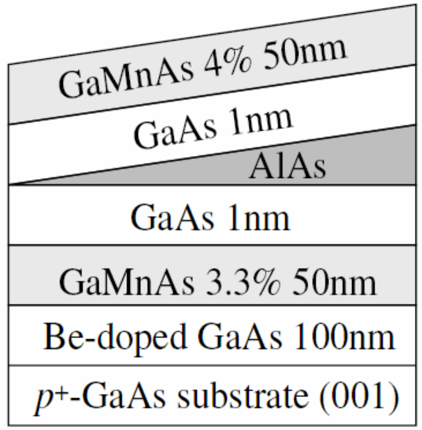


Spiral exchange coupling across the DMS junction with sensitive T dependence.

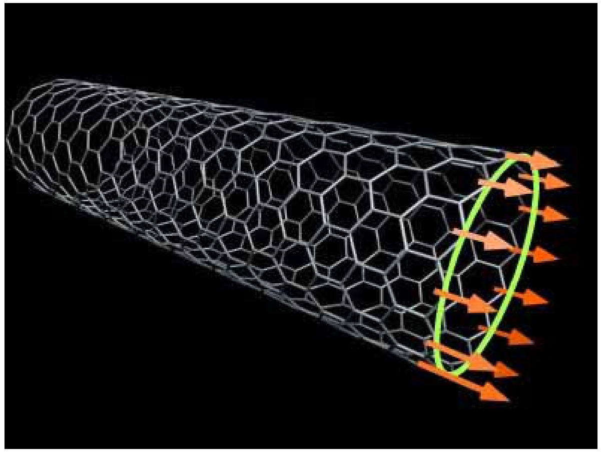
This oscillatory behavior implies the transport across the junction can be manipulated by temperature, gate voltage ans other means!!

Nanoscience Meets Spintronics…

Nanostructure is often built for devices based on existing bulk properties. Or, sometimes, it is used as a powerful tool to enhance the desired bulk properties.



Lin, Oshikawa, Refael (2004)

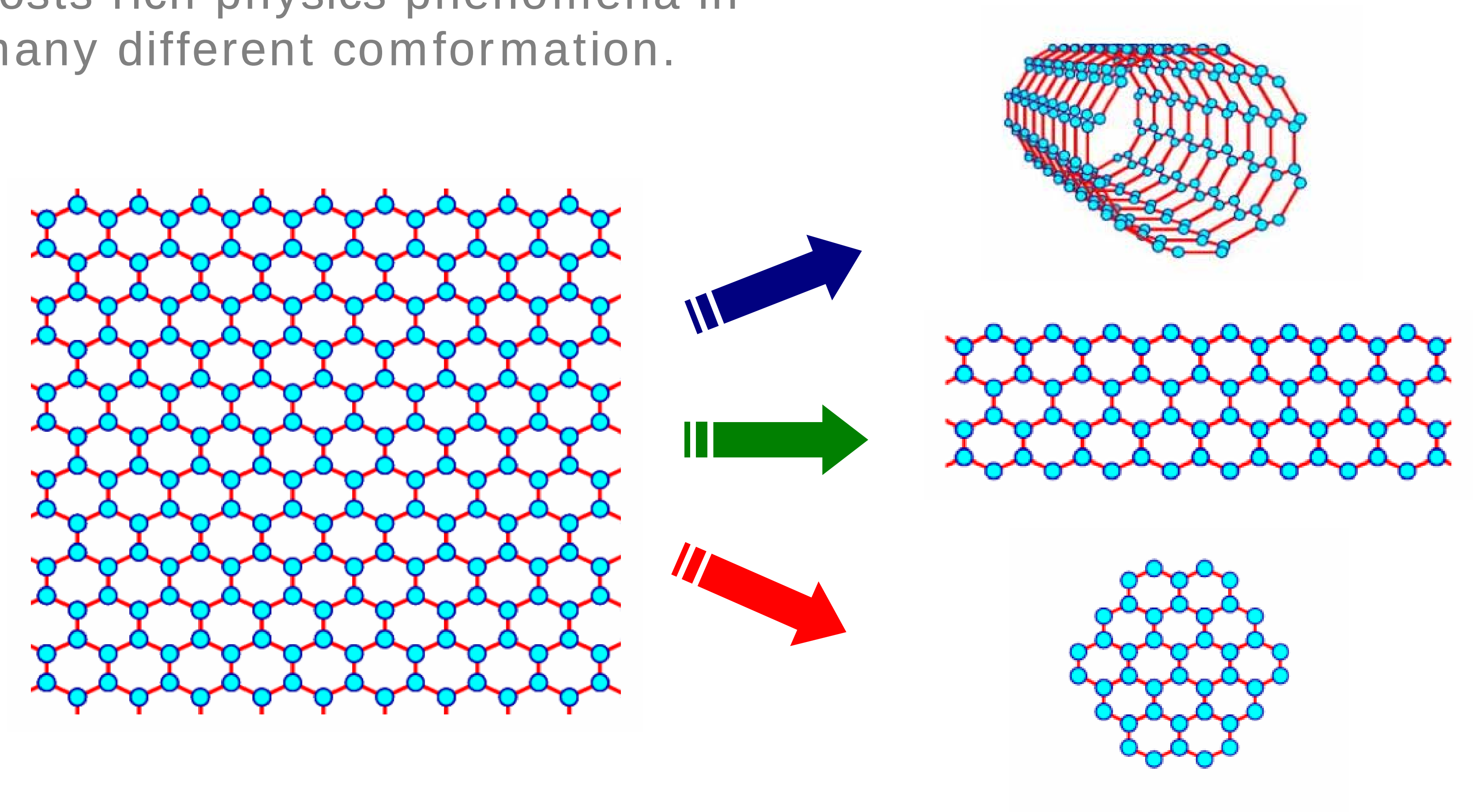


Zigzag carbon nanotube turns magnetic at the open edge

BUT! The bulk properties sometimes change dramatically when the system size shrinks. Can we make use of the novel changes at nanoscale somehow?

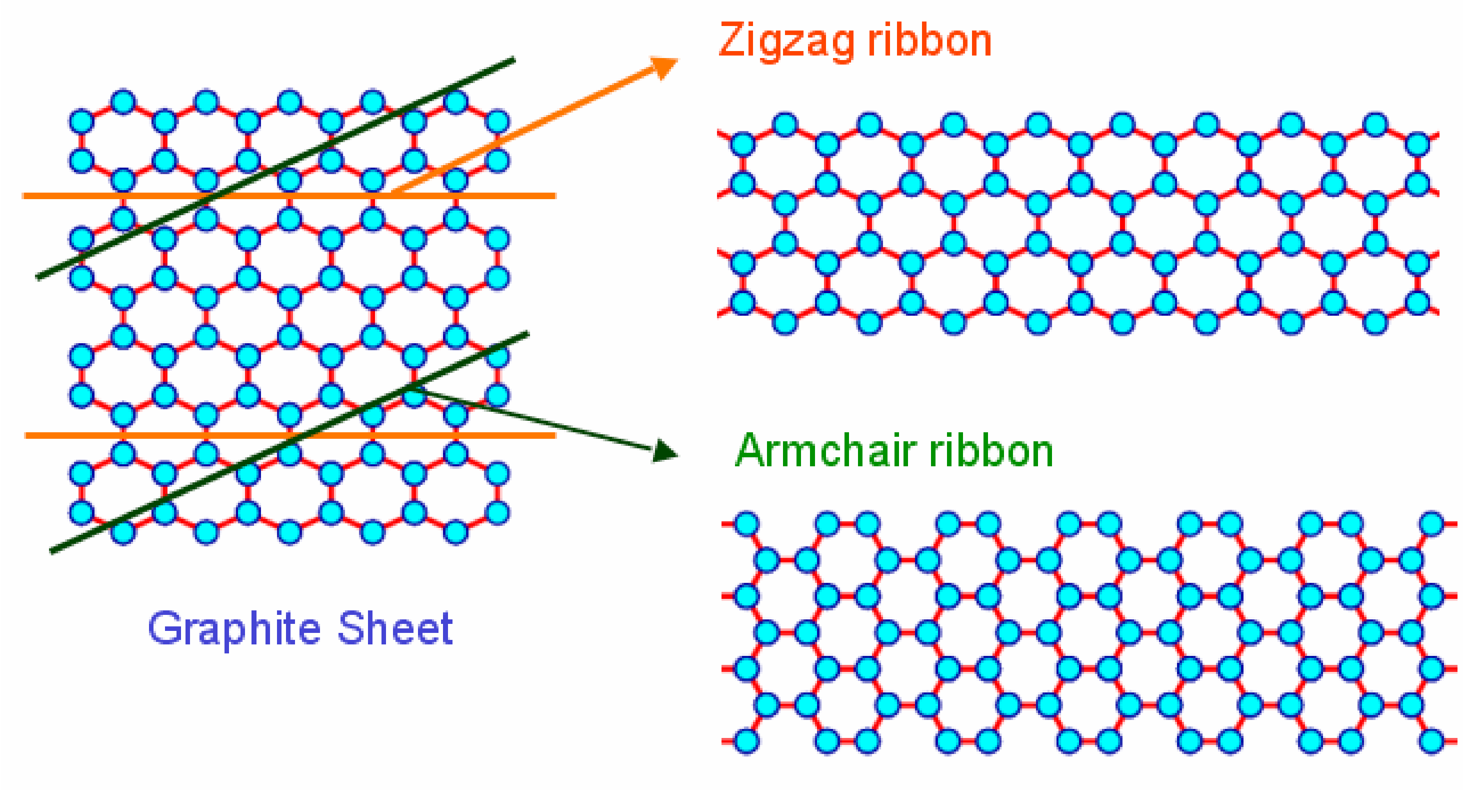
Carbon Nanoribbon

Carbon network (honeycomb lattice) hosts rich physics phenomena in many different comformation.



Armchair v.s. Zigzag

At nanoscale, the slight difference in edge topology changes the low-energy physics completely!!



Nanoibbon Fabrication

Peak for graphite structure!

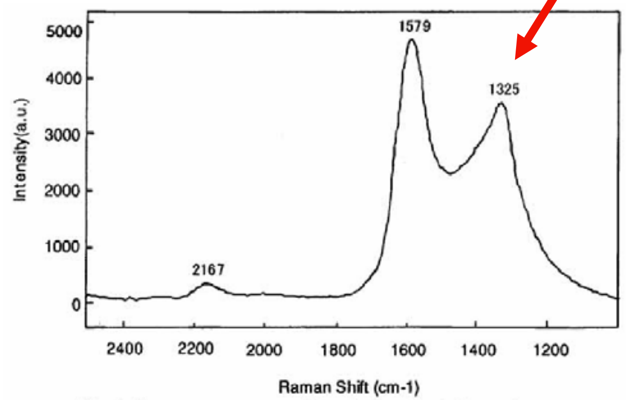


Fig.1. Raman spectrum of the defluorinated specimen

Synthetic Metal **121**, 1237 (2001);
ibid., **135-136**, 785 (2003).

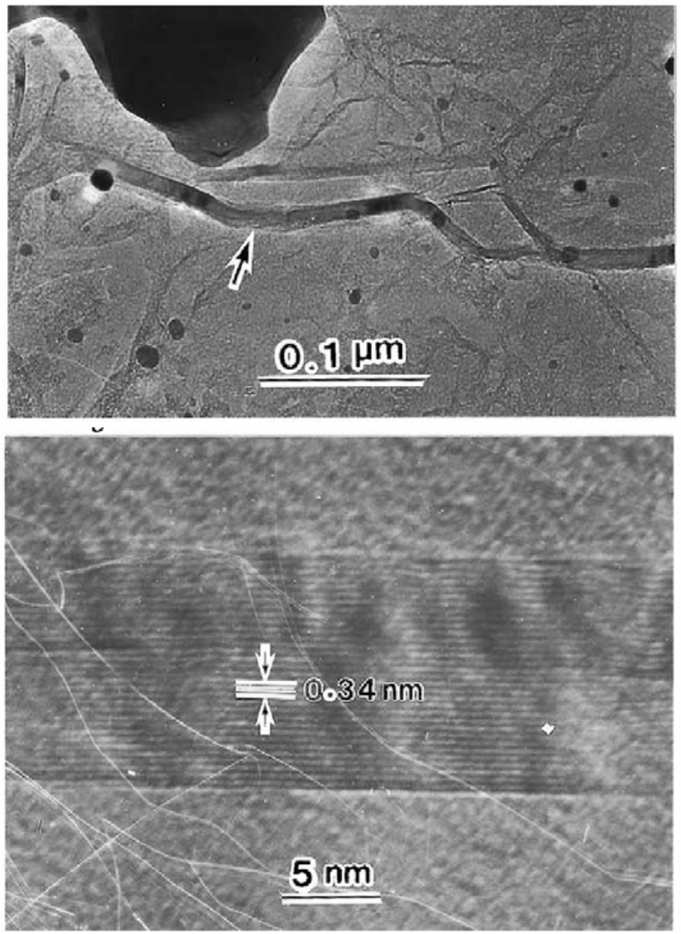
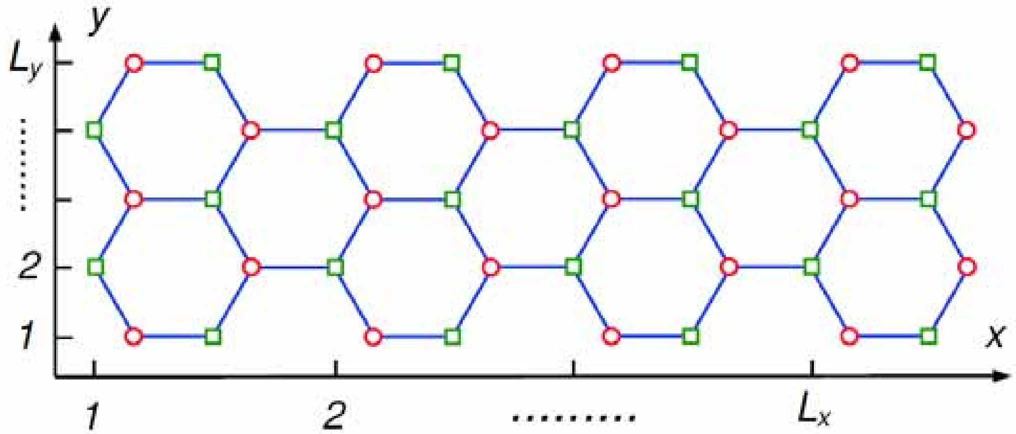


Fig.3 High resolution TEM showing a lattice image of the (002) face having a distance of 0.34 nm of a ribbon-shaped nanographite.

Carbonization of polyacetylene thin film by pyrolysis and e-beam irradiation.

Lattice Hamiltonian



We model the armchair nanoribbon with the Hubbard Hamiltonian, $H = H_t + H_U$,

$$H = -t \sum_{\langle \mathbf{r},\mathbf{r}' \rangle,\alpha} [c^{\dagger}_{\alpha}(\mathbf{r}) c_{\alpha}(\mathbf{r}') + \text{H.c.}] + U \sum_{\mathbf{r}} n_{\uparrow}(\mathbf{r}) n_{\downarrow}(\mathbf{r}),$$

where t is the hopping amplitude on the honeycomb network, $U > 0$ is the on-site repulsion.

Band Structure

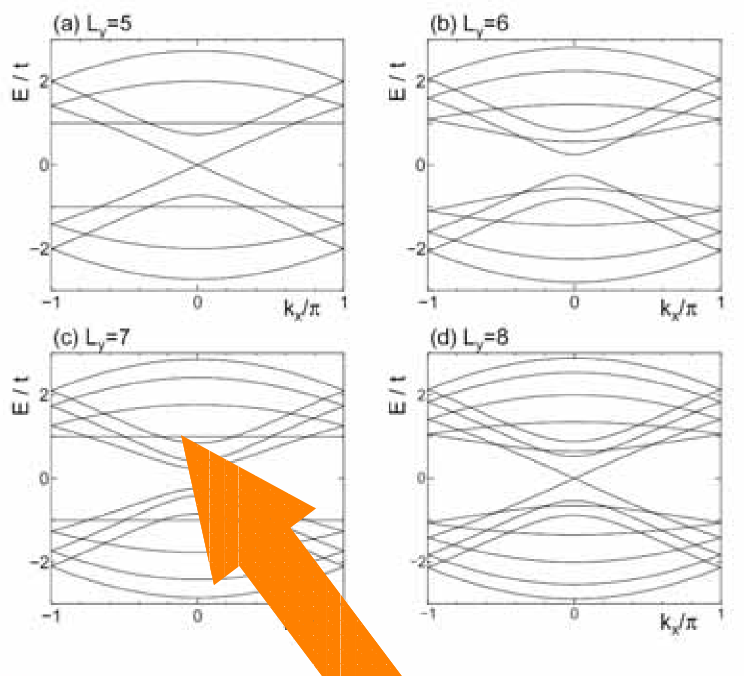


FIG. 2: Band structure for finite armchair NRs of different width $L_y = 5, 6, 7, 8$.

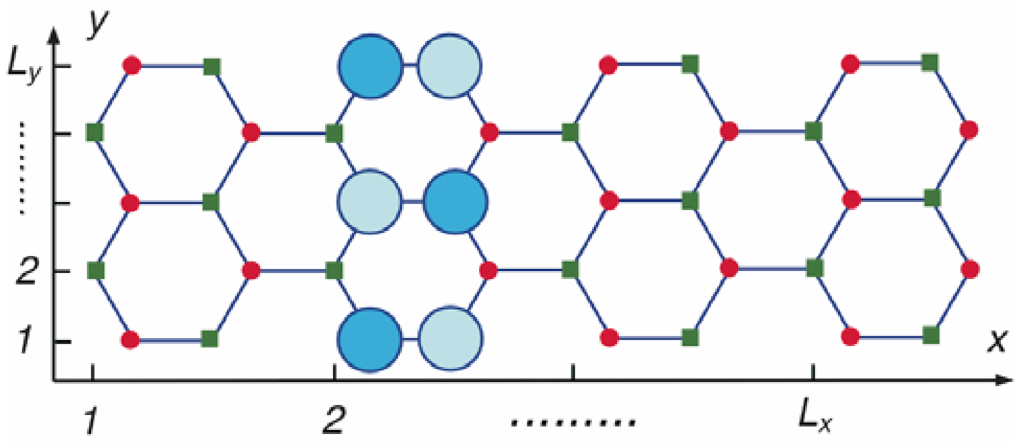
Ignore the repulsive interaction U first. The tight-binding hopping Hamiltonian can be solved easily.

The band structures are rich and complex, depending on the width of the armchair nanoribbons.

For *odd Ly*, there exists flat bands, intersecting with several 1D conducting channels.

Wannier Orbitals in Flat Band

It is rather remarkable that the local orbital does not “hop around” because of the ***perfect destructive quantum interferences***.

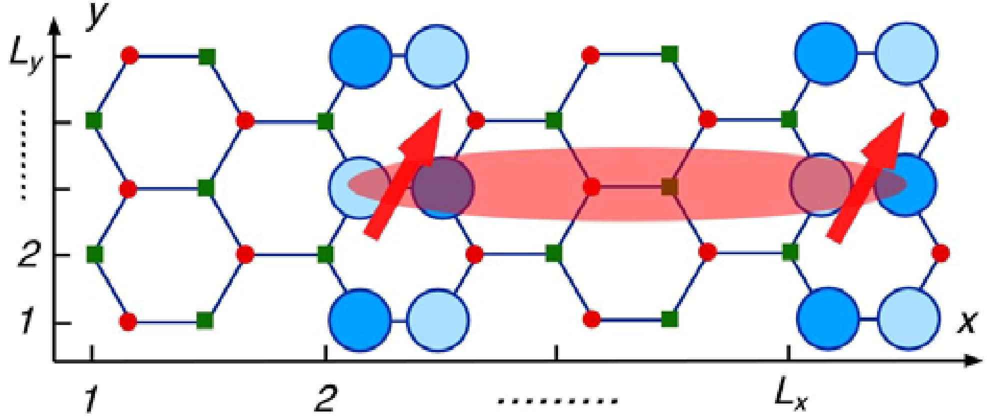


The local Wannier orbital at $x = x_0$ in the flat band takes the simple form,

$$\Phi_F(x,y) = \Phi(x)\begin{bmatrix} \varphi_A(y) \\ \varphi_B(y) \end{bmatrix} = \delta_{x,x_0}\frac{1}{\sqrt{L_y+1}}\begin{bmatrix} \sin(\pi y/2) \\ \mp\sin(\pi y/2) \end{bmatrix}$$

Ferromagnetism in Nanoribbon

On-site repulsive interaction U prefers each orbital is partially filled -> ***birth of local magnetic moments in the flat band!!*** However, it is not Mielke-Tasaki flat-band ferromagnetism due to zero overlap between neighboring local orbitals.



The presence of itinerant carriers mediate the exchange interaction between two local moments,

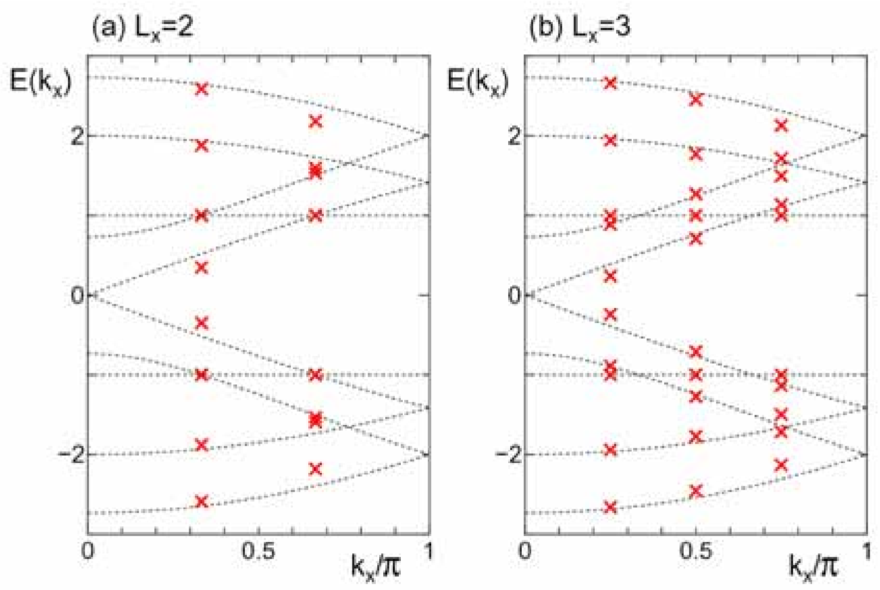
$$H_{ex} = J_{12}\ \boldsymbol{S}_1 \cdot \boldsymbol{S}_2,$$

where $J_{12} < 0$ indicating the ferromagnetic coupling.

Finite-Size Effect

We found the energy spectrum for finite armchair nanoribbon is well approximated by the following quantization rule,

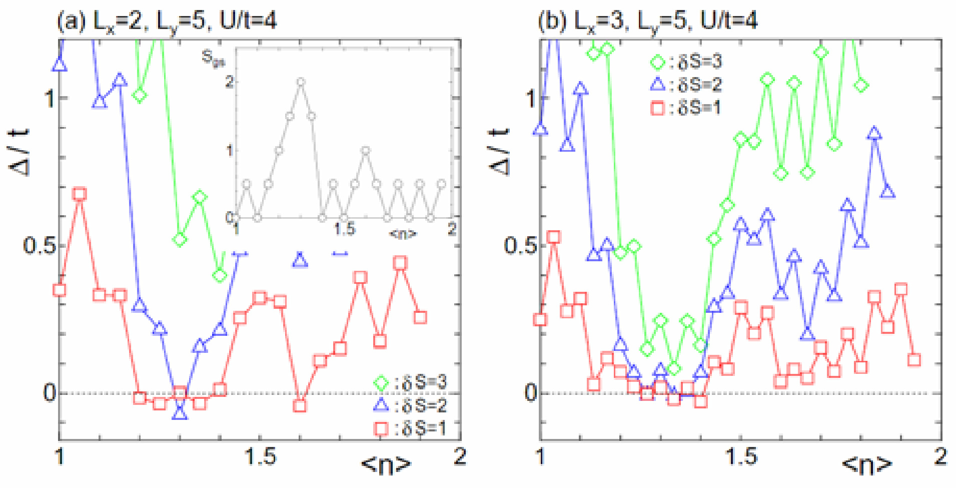
$$k_x = \frac{2n\pi}{L_x + 1}, \qquad k_y = \frac{2m\pi}{L_y + 1}.$$



For Lx=2, ***there are gapless itinernat carriers*** -> ferromagnetic ground state!!

For Lx=3, ***no gapless itinerant carriers around*** -> Curie-like paramagnetic state.

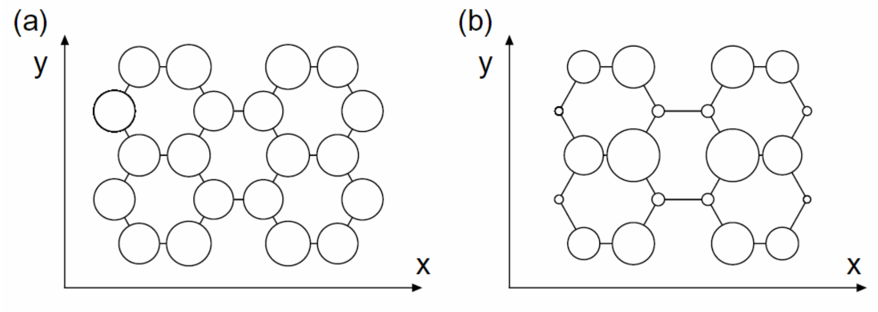
Flat-band Ferromagnetism



The predictions are verified by non-Abelian density-matrix renormalization group (DMRG) calculations!!

The spatial profile of spin density is very close to the local ***Wannier orbital s*** *!!*

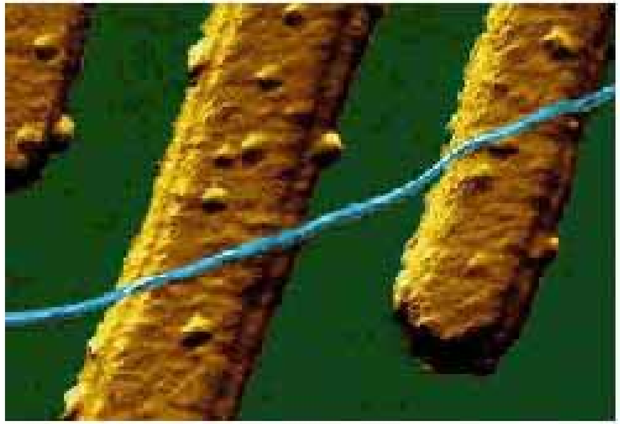
Somehow the weak-coupling theory works rather well even in the strong coupling.

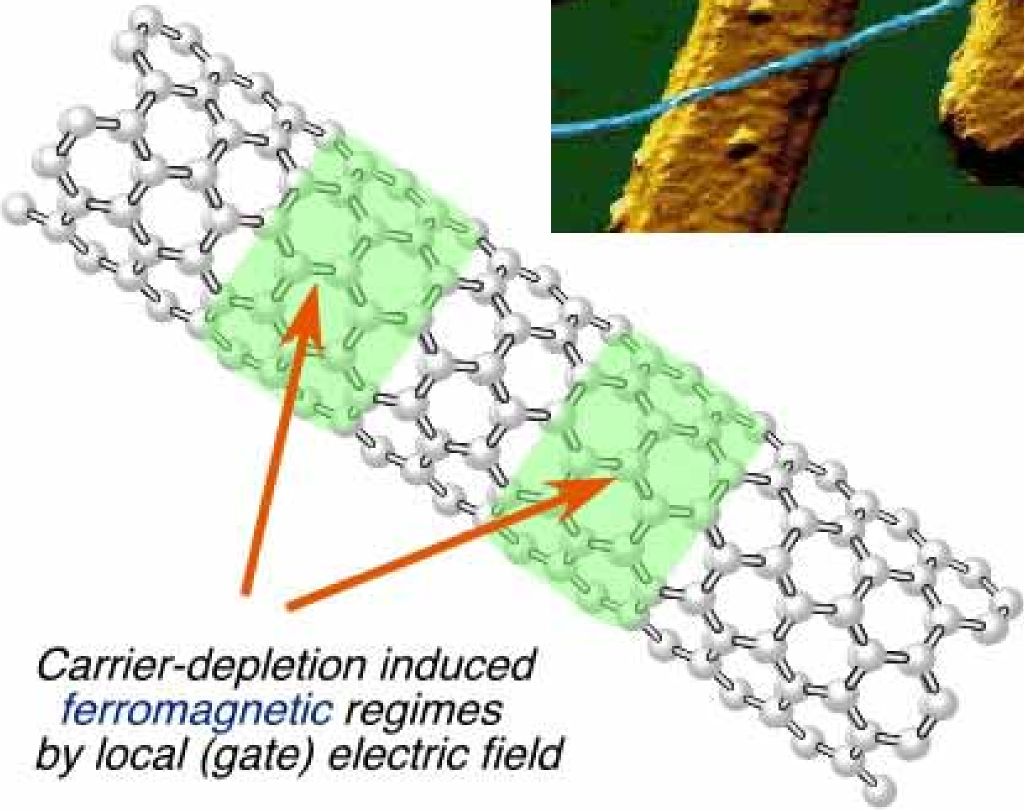


Charge density ***Spin density***

Nanotube Junction

The flat-band ferromagnetism might have a chance to be realized in armchair carbon nanotube too!!





Ferromagnetism in Organic Polymer

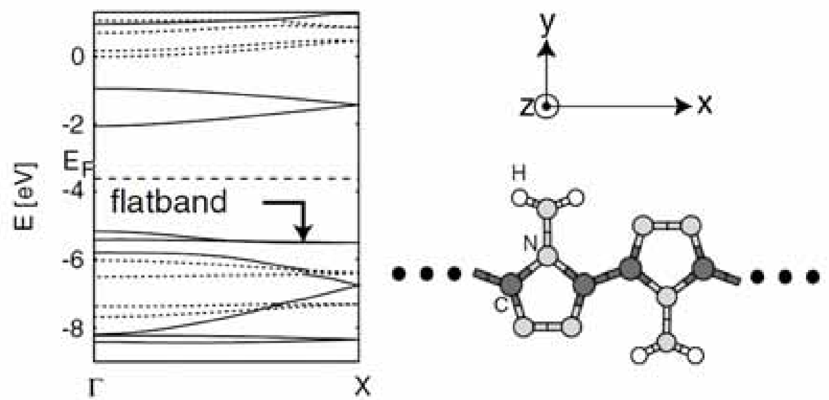


FIG. 2. The band structure (left panel) and the optimized atomic configuration (right) of the (undoped) polyaminotriazole obtained by the GGA-DFT. The solid (dotted) lines represent bands having π (σ) character.

Arita *et al.*,
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It was proposed that the organic polymer with five-member rings (polyaminotriazole) becomes ferromagnetic upon appropriate doping. The doping can be achieved either chemically or by field-effect approach.

The ferromagnetism is driven by Mielke-Tasaki mechanism through the non-vanishing overlaps between Wannier orbitals.

FIG. 1. The chain of five-membered rings, where the shading indicates a Wannier orbital that satisfies the local connectivity condition.

Remarks

- ***Spintronics is a multidisciplinary field.***
- ***Green's function approach opens up the question whether the spin-wave excitation is sharp.***
- ***Transport through DMS might exhibit novel oscillatory behavior versus T or gate voltage.***
- ***Nanoribbon/Nanotube may be the fun playground to explore nanospintronics!***