Electron spin

- Was first introduced in 1925 by Uhlenbeck and Goudsmit to explain the hyperfine structure of the atomic spectrum.

- A theoretical foundation has been provided in 1928 by Dirac by making a relativistic correction to the wave equation.

[Video link: https://www.youtube.com/watch?v=28Xe4FCCjtg]

1. Explain what electron spin is. Introduce magnetoresistance. Give example of magnetoresistance in a material or system. What is role of electron spin in magnetoresistance of materials? What is spintronics?
Discovery of electron spin

The discovery note in Naturwissenschaften is dated Saturday 17 October 1925. One day earlier Ehrenfest had written to Lorentz to make an appointment for the coming Monday to discuss a "very witty idea" of two of his graduate students. When Lorentz pointed out that the idea of a spinning electron would be incompatible with classical electrodynamics, Uhlenbeck asked Ehrenfest not to submit the paper. Ehrenfest replied that he had already sent off their note, and he added: "You are both young enough to be able to afford a stupidity!"

Ehrenfest's encouraging response to his students ideas contrasted sharply with that of Wolfgang Pauli. As it turned out, Ralph Kronig, a young Columbia University PhD who had spent two years studying in Europe, had come up with the idea of electron spin several months before Uhlenbeck and Goudsmit. He had put it before Pauli for his reactions, who had ridiculed it, saying that "it is indeed very clever but of course has nothing to do with reality". Kronig did not publish his ideas on spin. No wonder that Uhlenbeck would later refer to the "luck and privilege to be students of Paul Ehrenfest".

George Uhlenbeck (left) and Samuel Goudsmit (right) proposed the idea that each electron spins with an angular momentum of one half Planck constant and carries a magnetic moment of one Bohr magneton (1925).

https://www.lorentz.leidenuniv.nl/history/spin/spin.html
Spintronics

• Spintronics investigates control and manipulation of the electron spin in metals and semiconductors.
• Anisotropic magnetoresistance effect (AMR) was used in the magnetic read heads of earlier generations.
• In nanostructures spin polarization of the current adds a dramatic new functionality establishing polarization-based electronic circuits in addition to charge-based circuits.
• Current and future applications range from spin-based field effect transistors (FETs), through permanent magnetic storage devices without moving parts like read/write heads, to quantum computers.
• Due to much larger scattering length, spin is superior to charge in terms of coherent effects and for quantum computation applications.

2. Give examples of spintronics applications. What is spintronics advantage comparable with conventional (charge) electronics? Why could spin be more effective than charge?
**Magnetoresistance**

Magnetoresistance (MR) is the change of resistance of a conductor in an external magnetic field.

In typical metal, at room temperature, orbital MR effects are very small, at most of the order of a few per cent.

\[
\frac{\Delta \rho_{xx}}{\rho_{xx}} = \frac{\rho_{xx}(B) - \rho_{xx}(0)}{\rho_{xx}} \sim (\omega_c \tau)^2 \ll 1
\]

Comment: For a spherically-symmetric energy spectrum

\[
\rho = \begin{pmatrix}
\rho_{xx} & \rho_{yx} \\
\rho_{xy} & \rho_{yy}
\end{pmatrix} = \frac{1}{\sigma_0} \begin{pmatrix}
1 & -\omega_c \tau \\
\omega_c \tau & 1
\end{pmatrix}
\]

Therefore, the xx-component is field-independent. However, energy spectrum of realistic metals is anisotropic.

3. Is orbital magnetoresistance large in typical metals at room temperature? How does xx component of longitudinal resistance depend on field in two-dimensional electron gas? Can you derive its value from the conductance matrix?
Diffusive transport

Between scattering events electrons move like free particles with a given effective mass.

In 1D case the relation between the final velocity and the effective free path, $l$, is then

$$v^2 - v_0^2 = -2 \frac{eE}{m^*} l$$

Assuming $v = v_0 + v_d$ where $v_d$ is the drift velocity while $v_0$ is the typical velocity and introducing the collision time as $\tau = l/v_0$ we obtain in the linear approximation:

$$v_d = \frac{e\tau}{m^*} E$$

Mobility
Diffusion motion of electron in magnetic field

\[ v_d = \frac{-e\tau}{m^*} E \quad \rightarrow \quad j = -env_d = \frac{ne^2\tau}{m^*} E \]

In magnetic field

\[ \frac{d^2 \vec{r}}{dt^2} + \frac{\vec{v}_d}{\tau} = -\frac{e}{m^*} \left( \vec{E} + \vec{v}_d \times \vec{B} \right) \]

“friction”  Lorentz force

\[ \vec{j} = \sigma \left( \vec{E} + \vec{v}_d \times \vec{B} \right) \]

\[ \omega_c \tau \leq 1 \]
Conductivity tensor

Magnetic field is applied in the $z$-direction, $\mathbf{B} = (0, 0, B)$

$$
\begin{align*}
  j_x &= \sigma E_x + \sigma v_y B = \sigma E_x + \frac{ne^2 \tau}{m^*_e} v_y B = \sigma E_x - j_y \omega_c \tau \\
  j_y &= \sigma E_y - \sigma v_x B = \sigma E_y - \frac{ne^2 \tau}{m^*_e} v_x B = \sigma E_y + j_x \omega_c \tau \\
  j_z &= \sigma E_z \\
  \omega_c &= \frac{eB}{m^*} 
\end{align*}
$$

Here $v_i$ are the components of the drift velocity vector. Solving this system of equations for $j$ gives $j = \sigma \mathbf{E}$ with conductivity as a tensor,

\[
\sigma = \frac{1}{1 + \omega_c^2 \tau^2} \begin{pmatrix}
  1 & -\omega_c \tau & 0 \\
  \omega_c \tau & 1 & 0 \\
  0 & 0 & 1 + \omega_c^2 \tau^2
\end{pmatrix}
\]

Resistivity (inverse to conductivity) tensor: $\hat{\rho} = \sigma^{-1}$

$$
\rho_{xx} = \frac{\sigma_{xx}}{\sigma_{xx}^2 + \sigma_{xy}^2}, \quad \rho_{xy} = -\frac{\sigma_{xy}}{\sigma_{xx}^2 + \sigma_{xy}^2}
$$

Important quantity is the product of the cyclotron frequency, $\omega_c = \frac{eB}{m^*_e}$ by the relaxation time, $\tau$

\[
\begin{pmatrix}
  V_x \\
  V_y
\end{pmatrix} = \begin{pmatrix}
  \rho_{xx} & \rho_{xy} \\
  -\rho_{xy} & \rho_{xx}
\end{pmatrix} \begin{pmatrix}
  I_x \\
  I_y
\end{pmatrix} \cdot s
\]

\[
\begin{pmatrix}
  I_x \\
  I_y
\end{pmatrix} = \begin{pmatrix}
  \sigma_{xx} & \sigma_{xy} \\
  -\sigma_{xy} & \sigma_{xx}
\end{pmatrix} \begin{pmatrix}
  V_x \\
  V_y
\end{pmatrix} \cdot \frac{1}{s}
\]
Magnetic field on nanoscale

It is not difficult to get large fields going to nanometer scale.
The MR effect has been of substantial importance technologically, especially in connection with read-out heads for magnetic disks and as sensors of magnetic fields. The most useful material has been an alloy between iron and nickel, Fe_{20}Ni_{80} (permalloy).

The general consensus in the 1980s was that it was not possible to significantly improve performance of magnetic sensors based on MR.
Tunneling magnetoresistance

‘Tunnel magnetoresistance (TMR) is a magnetoresistive effect that occurs in a magnetic tunnel junction (MTJ), which is a component consisting of two ferromagnets separated by a thin insulator.’

‘The effect was originally discovered in 1975 by M. Jullière (University of Rennes, France) in Fe/Ge-O/Co-junctions at 4.2 K. The relative change of resistance was around 14%, and did not attract much attention. In 1991 Terunobu Miyazaki (Tohoku University, Japan) found an effect of 2.7% at room temperature. Later, in 1994, Miyazaki found 18% in junctions of iron separated by an amorphous aluminum oxide insulator and Jagadeesh Moodera found 11.8% in junctions with electrodes of CoFe and Co. The highest effects observed to date with aluminum oxide insulators are around 70% at room temperature.’

https://en.wikipedia.org/wiki/Tunnel_magnetoresistance

4. Introduce effect of tunnelling magnetoresistance (TMR). What are the materials suitable for tunnelling magnetoresistance devices? Explain how TMR works and how to make tunnel magnetoresistance junctions. What are current and expected applications of TMR?
Tunneling magnetoresistance

Here the insulator should be only a few atomic layers thick so that there is a significant probability that electrons can quantum mechanically tunnel through the insulating barrier.

- Fe/amorphous Ge/Co, Ni/NiO/(Fe,Co,Ni), CoFe / Al₂O₃ /Co, Fe /Al₂O₃/ Fe,
- Fe/MgO/Fe - TMR can exceed 200%

Due to the better performance of the magnetic tunnel junctions they are expected to become the material of choice for technical applications.

Their use for non-volatile magnetic random access memories (MRAM) is of particular interest - MRAM systems based on TMR are already on the market.

One expects that TMR based technologies will become dominant over the GMR sensors.

4. Introduce effect of tunnelling magnetoresistance (TMR). What are the materials suitable for tunnelling magnetoresistance devices? Explain how TMR works and how to make tunnel magnetoresistance junctions. What are current and expected applications of TMR?
Spin interacts only weakly with its environment. The majority of the electron scattering events are spin-conserving, and it can therefore be expected that spin is conserved over distances that are much larger than the elastic mean free path. Key parameter in spintronics is spin polarization which could be defined as:

\[ P_q = \frac{q_\uparrow - q_\downarrow}{q_\uparrow + q_\downarrow} \]

↑ and ↓ denote the majority and the minority spin, respectively. For \( q_\downarrow = 0 \), polarization \( P_q = 1 \); while for \( q_\downarrow = q_\uparrow \), \( P_q = 0 \).

TMR refers to the resistance of a ferromagnet-insulator-ferromagnet (FIF) tunnel junction in which coercive magnetic fields differ by a significant amount, which allows the relative orientation of the magnetizations to be changed by sweeping a magnetic field aligned parallel to the layers. It was found that, for the magnetizations of the two layers aligned parallel to each other, the tunnel resistance is lower than for antiparallel alignment.

5. What is spin polarization? Write its expression. What is effect of spin polarization on tunnelling magnetoresistance? Is tunnel resistance lower for antiparallel alignment of spins?
Effect of spin polarization

Magneto-resistance of a TMR structure formed by a CoFe-Al$_2$O$_3$-Co sandwich, with the magnetization directions of the two films as indicated in the schemes (bottom) Also shown in the top two traces are the much weaker anisotropic magneto-resistances of the corresponding individual films.

‘The upper two curves show the small magnetoresistance changes in the two films (not the junction) which mark the coercive fields ($H_c$) by the position of their extrema. (The presence of a maximum or minimum is determined by the field and current directions.)’

The tunnel resistance is lower for parallel alignment.
We define conductances $G_p$ and $G_{ap}$ for the parallel and antiparallel configurations. The densities of states for the source and drain ferromagnetic electrodes are labeled $D_{↑(↓)}^S$ and $D_{↑(↓)}^D$.

$$G_p \propto D_{↑}^S D_{↑}^D + D_{↓}^S D_{↓}^D$$
$$G_{ap} \propto D_{↑}^S D_{↓}^D + D_{↓}^S D_{↑}^D$$

Since, in a ferromagnet, $D_{↑} > D_{↓}$, we have $G_p > G_{ap}$.

The tunneling magnetoresistance (TMR) is usually defined as:
Here $R_{ap,p}$ denotes the resistance of the corresponding configurations.
Inserting the conductances gives:
Here $P$ denotes the polarization of the density of states. In cobalt, for example, $P_{Co} = 0.34$, which gives a TMR of 0.26 in an ideal system.

$$TMR = \frac{2P_S P_D}{1 - P_S P_D}$$

6. Link conductance and polarization. How is tunnelling magnetoresistance (define it) expressed through the polarization of source and drain? Give an example of ideal TMR value for a metal, for instance, cobalt.
In a magnetic random access memory (MRAM) chip, each bit is stored in a sequence of TMR layers. The lower ferromagnetic layer is hard, i.e. not reversible by the magnetic fields acting on the layers. The spin state of upper layer can be changed by current.

The square arrays of TMR columns are contacted by one-dimensional arrays of wires on the top and on the bottom, which are rotated by $90^\circ$ with respect to each other. In this way, each element of the array can be addressed individually. The writing, which means defining the orientation of the top magnetic layer, can be done by current pulses.

The memory can be read out without a magnetic read head. Two states of the bit correspond to the two values of the measured current through tunnel junction. No moving parts are required. The stored data does not get lost when the power is turned off.

7. Explain how tunnelling magnetoresistance can be used in memory chips? Is hard ferromagnetic layer necessary in their construction? Is yes, why? How to assemble a sequence of TMR elements and how to write and read information? Are movable parts necessary? Are stored data lost when the power is turned off?
TMR based memory chips

Applications: - read heads of Hard Disc Drive
- M-RAM (Magnetic Random Access Memory)

MRAM: density/speed of DRAM/SRAM + nonvolatility + low energy consumption

Dynamic random-access memory
Static random-access memory
Giant magnetoresistance

In GMR, as in TMR resistance depends on the relative orientation of the magnetizations of the ferromagnetic layers. Replace the insulator in a TMR layer sequence by a normal metal, and you have a GMR structure. It has been established that resistance dependence originates mostly from spin-dependent transmission of the conduction electrons across the ferromagnet-normal metal interfaces.

8. Introduce phenomenon of giant magnetoresistance (GMR). In what systems does it take place? What are materials suitable for GMR devices and how are they used? What is the difference between GMR and TMR?
Giant magnetoresistance structures

Fe/Cr/Fe trilayer, P. Grünberg, room temperature

(FeCr)n, n=60. A. Fert, Liquid He temperature
The GMR effect as observed on a Fe-Cr-Fe sandwich structure. The anisotropic magnetoresistance of a ferromagnetic thin film is shown in comparison.

In the parallel configuration, the highly transmissive spin channel dominates the resistance; whereas, in the antiparallel configuration, both spin channels contribute equally to the resistance. This results in a lower overall resistance for the parallel configuration.

8. Introduce phenomenon of giant magnetoresistance (GMR). In what systems does it take place? What are materials suitable for GMR devices and how are they used? What is the difference between GMR and TMR?
Non-magnetic state:
numbers of spin-up and spin-down electrons are equal

Ferromagnetic state:
numbers of spin-up and spin-down electrons are different

\[ s = \frac{N_{\uparrow} - N_{\downarrow}}{N_{\uparrow} + N_{\downarrow}} \]
Antiferromagnet trilayer system, $H=0$

Shown are DOS for up- and down- spins

Equivalent circuit diagram

$$R = (1/2)(R_{\uparrow} + R_{\downarrow})$$

Magnetic field aligns the magnetic moments of the layers

12. Explain physics of GMR introducing equivalent circuit diagrams. What is the difference in resistance between parallel and antiparallel orientations? Is any way to enhance GMR using half-metals?
Spin aligned layers

Ferromagnet trilayer system, $H \neq 0$

Shown are DOS for up-and down-spins

\[ R = \frac{2R_\uparrow R_\downarrow}{R_\uparrow + R_\downarrow} \]

\[ \Delta R = -\frac{1}{2} \left( \frac{R_\uparrow - R_\downarrow}{R_\uparrow + R_\downarrow} \right)^2 \]
A way to enhance GMR: Half-metals

We are interested in the largest possible difference in the Fermi-level DOS for spin up and spin down.

In half-metals the spin down band is metallic while the spin up band is an insulator (example - CrO$_2$).
Half-metals GMR

No electric current (spin blockade)

Only spin down current
Ferromagnetic metals

3d transition metals - Fe, Co, Ni; lantanides (4f) - Gd

The origin of magnetism - behavior of the 3d/4f electrons, respectively. We will focus on 3d elements.

In the free atoms, the 3d and 4s levels of the 3d transition elements are hosts for the valence electrons.

In the metallic state these 3d and 4s levels are broadened into energy bands.

4s orbitals are rather extended → overlap between 4s orbitals of neighboring atoms → 4s band is spread out over a wide energy range (15-20 eV).

3d orbitals are much less extended in space → associated 3d energy band is comparatively narrow (4-7 eV).

4s electrons are much more mobile than 3d ones.

11. How do different spin states influence resistance of a material? How do 4d-electron states contribute to the resistance? What are requirements for building magnetic superlattices for GMR devices? How to engineer magnetic materials using principle of Friedel oscillations? How do electrons in non-magnetic layers provide coupling between magnetic layers?
Energy of the state depends on the interplay between the (exchange) interaction between electrons and their kinetic energy.

The Exchange Interaction:
arises from Coulomb electrostatic interaction and the Pauli exclusion principle

\[ \mathcal{H} = -2J_{ab} \vec{S}_1 \cdot \vec{S}_2 \]

→ we can write

Higher repulsion energy

Lower repulsion energy
Exchange interaction

**More general**
By keeping the orbital components fixed.
Orbitals \( i, j \)
\[
\mathcal{H}_{\text{exch}} = - \sum_{i,j} J_{ij} \vec{S}_i \cdot \vec{S}_j
\]
exchange Hamiltonian

Exchange interaction requires **overlap of wave functions**.
Magnetic impurities

Imperfections (defects and impurities) in metals become screened by the surrounding conduction electrons.

The imperfection gives rise to decaying (Friedel) oscillations of the electron density as a function of the distance from the disruption.

Similarly, a magnetic impurity atom in a metal gives rise to an induced spin polarization of the electron density.

With increasing distance from the magnetic impurity there will be an oscillation in the sign of the polarization and the disturbance will also decay in magnitude with distance.

As a consequence, the magnetic moment of a second impurity will become aligned parallel or antiparallel to the magnetic moment of the first moment depending on the sign of the induced polarization at that particular distance.
• Localized spin induces spin polarization of conduction electrons.
• This polarization decays in space in an oscillatory fashion – this is a property of magnetic susceptibility of the Fermi gas.
• Induced polarization interacts with second localized spin – indirect exchange or RKKY (Ruderman-Kittel-Kasuya-Yosida) interaction.

Depending on the distance, the RKKY interaction can be either ferromagnetic or antiferromagnetic!

Electrons in non-magnetic layers provide coupling between magnetic layers!
Itinerant magnetism

How much does it cost to create a FM state?

A transfer of spin down electrons from the spin down band into the spin up band leads to lowering of the total energy (a gain).

On the other hand, such a process requires a transfer of electrons from spin down levels below the initial Fermi energy, into spin up levels situated just above the initial Fermi energy. That will increase the total energy (a loss).

Thus there is a competition between two opposite effects. This can be formulated as the so called Stoner criterion for ferromagnetism,

\[ J \, N(E_F) \geq 1 \]

Here \( J \) is called the Stoner exchange parameter and \( N(E_F) \) is the density of states at the Fermi energy.

10. Explain the concept of itinerant magnetism. Does itinerant magnetism important for giant magnetoresistance? In what materials does it takes place and what orbitals are most important for this effect? What role does exchange interaction play in itinerant magnetism? What is the Stoner criterion for ferromagnetism? Do you know a metal, which is on the verge of ferromagnetism?
Resistivity for different spin states

Conductivity of d transition elements is mainly determined by the 4s electrons (easily mobile due to the wide 4s energy bands).

However s electrons can scatter into the many d states which are available at the Fermi level → considerable resistance.

For Cu (following Ni in the Periodic Table) all the 3d states are situated below the Fermi level and therefore not available for scattering processes. This explains the particularly high conductivity of Cu.

Sir Nevil Mott, 1936

In a ferromagnet like Fe there are 2 types of carriers, one made up from spin up electrons and one from spin down electrons.

Since the density of states at the Fermi surface is quite different for the two spin states it follows that there is a significant difference in resistance for the spin up electrons and the spin down electrons.
It is important that the lattice parameters for the different layers match each other; it is also an advantage if the two metals forming the superlattice have the same crystal structure.

This is the case for Cr and Fe, where both metals adapt the bcc crystal structure and have very similar lattice spacing.

It was also extremely important that the spatial separation between the magnetic layers is of the order of nanometers.

In order to exhibit the GMR effect the mean free path for the conduction electrons has to greatly exceed the interlayer separations so that the electrons can travel through magnetic layers and pick up the GMR effect.
At present time, GMR structures can be also obtained by magnetron sputtering.
GMR effect and applications

A prerequisite for the discovery of the GMR-effect was provided by the new possibilities of producing fine layers of metals on the nanometer scale.

Originally, epitaxy was used. At present time, after Stuart Parkin, more simple and cheap method – sputtering – is more practical.

GMR effect can also be observed when the current flows parallel to the layers. One speaks of the current perpendicular to plane (CPP) and the current in plane (CIP) configurations. In spite being much weaker, CIP is an important configuration, since CPP has very small overall resistance.

13. Can GMR effect be observed when the current flows parallel to the layers? Explain physics of it. What are current-perpendicular-to-plane (CPP) and the current-in-plane (CIP) configurations? Why is CIP important?
Spin injection

The current density across the interface between a ferromagnet (F) and a normal conductor (N), is composed of two spin components, $j = j^\uparrow + j^\downarrow$. The spin current density is given by $j_s = j^\uparrow - j^\downarrow$. Here, we denote by $\uparrow$ the majority spin in the ferromagnet. In a normal conductor, there is no spin current associated with a charge current.

In the centre of normal conductor:

$$\sigma_{N\uparrow} = \sigma_{N\downarrow} = \frac{1}{2}\sigma_N$$

Close to interface:

$$j_{N\uparrow} = -\frac{\sigma_N}{2} \frac{1}{e} \frac{\partial \mu_{N\uparrow}}{\partial x} \equiv \beta_N j_N$$
$$j_{N\downarrow} = -\frac{\sigma_N}{2} \frac{1}{e} \frac{\partial \mu_{N\downarrow}}{\partial x} \equiv (1 - \beta_N) j_N$$

$\beta_N$ is the fraction of the current density carried by the spin-up channel in the normal metal.

Spin injection: spin transport in ferromagnet

In the ferromagnet, the two spin directions experience different conductivities:

Here $D_{F\uparrow(\downarrow)}(E_F)$ and $D_{F\uparrow(\downarrow)}$ denote the spin-resolved densities of states at the Fermi energy and the diffusion constants, respectively, while $\alpha_F$ represents the fraction of the total ferromagnet conductance that is contributed by the spin up channel.

The current in ferromagnet is split among the spin channels:

Here $\beta_F$ is the fraction of the current density carried by the spin-up channel in the ferromagnet.

Because in the normal metal, spin channels have equal conductances and in ferromagnet not, the spin accumulates close to the interface, and a spin density gradient builds up in both materials. This means that, in the interface region, the two spin directions have different electrochemical Potentials with 

$$\mu_{SF} \equiv \mu_{F\uparrow} - \mu_{F\downarrow}$$

and

$$\frac{\partial \mu_{SF}}{\partial x} = -\frac{e}{\sigma_{F\uparrow}} j_{F\uparrow} + \frac{e}{\sigma_{F\downarrow}} j_{F\downarrow}.$$
Spin injection: diffusion equation

By introducing spin-flip scattering times: the diffusion equation can be obtained

Here $n_{F\uparrow(\downarrow)}$ denotes the spin-resolved electron densities, $T_{\uparrow\downarrow}$ ($T_{\downarrow\uparrow}$) are the spin-flip scattering times from $\uparrow$ into $\downarrow$ (respectively, from $\downarrow$ into $\uparrow$) and $T_{1F}$ is the spin relaxation time.

**Diffusion equation:**

$$\frac{\partial^2 \mu_{SF}}{\partial x^2} = \frac{1}{D_F^{\text{eff}} T_{1F}} \mu_{SF}$$

$$D_F^{\text{eff}} = \frac{D_F\uparrow D_F\downarrow [D_F\uparrow(E_F) + D_F\downarrow(E_F)]}{D_F\uparrow D_F\uparrow(E_F) + D_F\downarrow(E_F) D_F\downarrow} = \alpha_F D_F\uparrow + (1 - \alpha_F) D_F\downarrow$$

**Diffusion equation solution:**

$$\mu_{SF}(x) = \begin{cases} \mu_{SF}(0) e^{x \lambda_F} & x \leq 0 \\ \mu_{SN}(0) e^{-x \lambda_N} & x \geq 0 \end{cases}$$

$$\lambda_F = \sqrt{D_F^{\text{eff}} T_{1F}}, \quad \lambda_N = \sqrt{D_N T_{1N}}$$

Here $\lambda_{F(N)}$ is the spin relaxation length in the corresponding material.
Spin injection: properties of interface

By solving current equations on both sides of interface and equalling currents, one can obtain:

\[
P_{jN}(x=0) = \frac{P_{jF}}{1 + (1 - P_{jF}^2)(\lambda_N/\sigma_N)(\sigma_F/\lambda_F)}
\]

Spin accumulation at the ferromagnet-normal metal interface, expressed in terms of the spin-resolved electrochemical potentials. The step of the averaged electrochemical potentials across the interface is denoted by \( \Delta \mu \).

For a ferromagnet with \( P_{jF} = 1 \), the spins are perfectly injected into the normal metal! To aim for a large spin polarization in the normal conductor, \( (\lambda_N/\sigma_N)/(\lambda_F/\sigma_F) \) should be as small as possible.

15. How are chemical potentials of differently polarized electrons linked in the interface? Write expression for the current polarization at an ferromagnet-normal metal interface. What is the condition of perfect injection of spins?
Spin injection: experiments

A spin-polarized current is injected from permalloy ($\text{Ni}_{80}\text{Fe}_{20}$) into copper, and a value of $P_{j,\text{Cu}} = 0.02$ was extracted. A spin-flip time $T_{1,\text{Cu}}$ of 42 ps was found at 4.2K, which corresponds to $\lambda_{\text{Cu}} \approx 1 \mu\text{m}$. Since the Drude scattering time in copper is 30 fs at 4.2K, these results show that the electrons experience 1000 elastic scattering events on average before they experience a spin flip. Even at room temperature, a relatively large value of $\lambda_{\text{Cu}} \approx 350 \text{ nm}$ remains.
Colossal magnetoresistance

‘Colossal magnetoresistance (CMR) is a property of some materials, mostly manganese-based perovskite oxides, that enables them to dramatically change their electrical resistance in the presence of a magnetic field. The magnetoresistance of conventional materials enables changes in resistance of up to 5%, but materials featuring CMR may demonstrate resistance changes by orders of magnitude. This technology may find uses in disk read-and-write heads, allowing for increases in hard disk drive data density.’

La$_{0.67}$Ca$_{0.33}$MnO$_3$  La$_{0.67}$Sr$_{0.33}$MnO$_3$

T$_{Curie}$ = 250 K  T$_{Curie}$ = 350 K

CMR materials are perovskites with crystal lattice that is very close to crystal lattice of high-temperature superconductors, for example, YBa$_2$Cu$_3$O$_x$.

Spin injection into YBa$_2$Cu$_3$O$_x$

1 - STO substrate (5 mm × 5 mm); 2 - YBCO; 3 - STO barrier; 4 - CMR; 5 - gold contact pads. The arrow shows the direction of the applied field.
Current dependence of the effect of spin injection

$\tau_p = 1 \mu s$
The annealing experiments, which change $T^*$ and the upper boundary of AFM spin fluctuations, display the removal of increase in resistance and coercive field effect.
Spin injection into ultrathinning films

The bilayer is set in the resistive state

Quasiparticle exchange has a considerable ab-plane component

YBCO film: 12-25 nm
Spin injection into ultrathing films

Both low-temperature and close-to-$T_c$ effects of spin injection are observed in ultrathing films
4-corners transport measurements

Montgomery technique
Faraday effect and magneto-optical imaging

The Faraday effect is a rotation of the polarization of light in presence of magnetic field. The effect was discovered by Michael Faraday in 1845.

https://en.wikipedia.org/wiki/Michael_Faraday
A differential MOI image showing the in-plane magnetization of the LCMO thin film surface. The sample is covered with an MO-indicator film and the red line indicates where the sample ends. The contrast in the image represents areas of strong and weak magnetic fields periodically alternating in the plane of the film and seen as bright and dark areas, respectively.
Anisotropy transport measurements

Temperature (K) vs. Resistance ($\Omega$)

- Red dashed line: parallel
- Black dotted line: perpendicular

LCMO

YBCO

STO

NANomaterials: Applications & Properties, 10 - 15 September 2017, Zatoka, Ukraine
Scanning electron microscopy and EDX confirm presence of both layers with reasonably well defined interface.
The main peak in x-ray diffraction scan is from the SrTiO$_3$-substrate. LCMO and YBCO are also identified in the scan. In addition, there are some unknown peaks that indicate significant inter-diffusion between the LCMO and YBCO forming interface layer with different properties than those of the pure compounds.
Magnetization measurements

![Magnetization measurements graph](image-url)
‘Carefully controlled interfaces between two materials can give rise to novel physical phenomena and functionalities not exhibited by either of the constituent materials alone.’

‘Here we examine superlattices composed of the halfmetallic ferromagnet La$_{2/3}$Ca$_{1/3}$MnO$_3$ and the high-temperature superconductor YBa$_2$Cu$_3$O$_7$ by absorption spectroscopy with circularly polarized X-rays and by off-specular neutron reflectometry. The resulting data yield microscopic insight into the interplay of spin and orbital degrees of freedom at the interface. The experiments also reveal an extensive rearrangement of the magnetic domain structure at the superconducting transition temperature.’
• An ex-situ YBCO/LCMO bilayer was investigated by a range of techniques.

• A strong anisotropy in resistance and a resistance peak is observed below critical temperature of superconductor.

• The resistance peak corresponds to stripy magnetic structure seen by magneto-optical imaging and registered by vibrating sample magnetometry.

• It is suggested that magnetic structure is associated with YBCO/LCMO interface.
Evidence of spin injection from $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ to $\text{YBa}_2\text{Cu}_3\text{O}_x$

Spin injection is most effective close to $T_c$

T. B. Hjelmeland et al.

Giant magnetoresistance
Evidence of spin injection from $\text{La}_{0.67}\text{Ca}_{0.33}\text{MnO}_3$ to $\text{YBa}_2\text{Cu}_3\text{O}_x$

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Datta-Das spin transistor

Spin-polarized electrons are injected in the semiconductor.

Gate is used to rotate the polarization plane (Rashba effect).

Ferromagnetic drain contact is used as analyzer.

No need to add/remove electrons – less energy consumption!

Spin FET is a modification of a GMR structure.

Idea by Datta & Das
Not realized experimentally


http://www.nims.go.jp/apfin/SpinFET.html

16. Introduce concept of Datta–Das spin transistor. Is it implemented? Does it use semiconductor? What are difficulties in injecting spins into semiconductor and what are possible solutions to overcome these difficulties? How can additional interface resistance in a tunnel barrier structure increase injected spin polarization?
Spin injection into semiconductors

It is difficult task because conductivity is lower than that of the ferromagnet and the spin-flip length is longer.

Two possible solutions: a) a ferromagnet with a spin polarization of $P_{jF} = 1$, b) inserting tunnel barriers at the ferromagnet-semiconductor interface to use spin-selective interface resistance.

**Interface tunnel barriers**

Additional interface resistance $R_{i↑(↓)}$ depends on spin and makes the spin-resolved electrochemical potentials discontinuous at the interface.
Detection of spin-polarized current

A frequently used technique is based on conversion of the spin polarization into circular polarization of photons, for example by a LED p-n type junction. During electron-hole recombination, the dipole selection rules allow only transitions between electron and hole states that emit photons of left or right circular polarization, with a weight given by the corresponding dipole matrix elements.

Selection rules for photon emission by electron-hole recombination in GaAs. The relative intensities and the orientation of the circular polarization are indicated at each transition.

The circularly polarized emitted light reflects the spin polarization of the injected current. $P_j = 0.13$ at the GaAs quantum well at a temperature of 4K is found, which decayed to 0.04 at 240K. The injected polarization at the interface was estimated to be as high as $P_j = 0.3$ and independent of the temperature.

17. How to detect spin-polarized current? Has it anything to do with circular polarization of photons? Can LED p–n type junctions be used for that? Please explain how. Do you know any spin-polarization experiments involving GaAs quantum wells? What polarization was observed there?
Ferromagnetic semiconductors

The Fermi energy in semiconductors is small compared to that in metals, and can become smaller than the spin splitting of the conduction band. This results in a spin polarization of 1. Consequently, the impedance mismatch problem would not occur.

Magnetization hysteresis curves of $\text{Ga}_{1-x}\text{Mn}_x\text{As}$.

A spin polarization of the current injected from $\text{Ga}_{1-x}\text{Mn}_x\text{As}$ into GaAs of $P_j = 0.82$ at liquid helium temperatures has been found. The impedance mismatch problem has been solved, at least conceptually.

18. What are ferromagnetic semiconductors? Do they help to solve the impedance mismatch problem? Can they have spin polarization equal to 1? How it can be achieved? Can Ga$_{1-x}$Mn$_x$As be used as a ferromagnetic semiconductor? What are the results of experiments with this compound?
The Rashba effect denotes the spin–orbit coupling experienced by moving electrons in electric fields. It can be induced by macroscopic electric field in a semiconductor quantum well. Due to the band offsets at the interface of two different materials the electrons are confined in a quantum well. A two-dimensional electron gas (2DEG) is formed. If the potential well is asymmetric, the electrons are moving in an effective electric field $E$. In the reference system of the electron this electrical field transforms into a magnetic field $B$. Depending of the spin orientation and the corresponding magnetic moment an energy lowering or an energy increase occurs, respectively. For applications it is essential, that the strength of the Rashba effect and thus the spin splitting can be controlled by means of a gate electrode.

19. What is Rashba effect? Can you explain its origin? Do you know any experimental observations of the Rashba effect? How could this effect be used in spin based field-effect transistor? What are the conditions for constructing Datta–Das transistor?
The Rashba effect is a direct result of inversion symmetry breaking in the direction perpendicular to the two-dimensional plane. Therefore, let us add to the Hamiltonian a term that breaks this symmetry in the form of an electric field

\[ H_E = -E_0 z \]

Due to relativistic corrections an electron moving with velocity \( \mathbf{v} \) in the electric field will experience an effective magnetic field \( \mathbf{B} \)

\[ \mathbf{B} = \left( \mathbf{v} \times \mathbf{E} \right)/c^2 \]

This magnetic field couples to the electron spin

\[ H_{SO} = \frac{g\mu_B}{2c^2} (\mathbf{v} \times \mathbf{E}) \cdot \sigma \]

where \( -g\mu_B\sigma/2 \) is the magnetic moment of the electron.

Within this toy model, the Rashba Hamiltonian is given by:

\[ H_R = \alpha (\sigma \times \mathbf{p}) \cdot \hat{z} \]

\[ \alpha = \frac{g\mu_B E_0}{2mc^2} \]

The eigenvalues are:

\[ \lambda_{\pm} = \frac{\hbar^2 k^2}{2m} \pm \eta k \]
This is a rotation along a circle formed by the intersection of the Bloch sphere with the plane given by $\phi$. In real space, the spinor rotates around the direction of the magnetic field seen by the electron, i.e. around the axis in the $(x, y)$ plane that is perpendicular to $\mathbf{k}$. For the above values, we find from $\Delta k_F L = 2\pi$ a rotation about $\pi$ over a distance $L$.

The Datta-Das transistor only works when the spin directions are well defined, which means that the channel should be quasi-one-dimensional. Second, the channel should be ballistic. Even though elastic scattering does not flip the spin, it changes the continuous spin rotation abruptly.
Spin relaxation and spin dephasing

One has to distinguish between two different time scales. First time scale $T_1$ comes from spin-up state experiencing a spin-flip scattering event and ending up in a spin-down state (or vice versa). Second time scale $T_2$ refers to the loss of the correlation of the spin precession around the quantization axis when it moves with the Larmor frequency $\omega_L = eB/2m^*$ around the effective magnetic field axis. It is also the time over which the superposition of two states, a situation encountered frequently in quantum computational schemes, decays into a pure state.

In Elliot-Yafet (EY) spin-orbit coupling mechanism, even spin-independent interactions can induce transitions between these eigenstates and generate spin dephasing. This type of spin relaxation increases both with the spin-orbit coupling and electron scattering rate. In GaAs, Elliot-Yafet spin relaxation is very strong for holes due to large spin-orbit coupling.

$$\tau_{s,\text{DP}} \propto \frac{(k_BT)^3}{\hbar^2 E_g} \frac{1}{\tau}$$

The Dyakonov-Perel (DP) mechanism emerges from the fact that the spin degeneracy is lifted in crystals without inversion symmetry. In contrast to the Elliot-Yafet mechanism, the dephasing occurs not during the scattering but during the electron motion in between these events. Because of this, the spin relaxation time is inversely proportional to the Drude scattering time.

By studying the spin relaxation time as a function of the mobility, one can easily distinguish between Elliot-Yafet and Dyakonov-Perel mechanisms.

$E$ is the energy of the electron and $\Delta_{SO}$ is the spin-orbit splitting.

20. Introduce spin relaxation and spin dephasing times. What mechanisms of spin relaxation do you know? What is their dependence on Drude scattering time?
Hyperfine interaction

It is an important source of spin relaxation, in which the spin-polarized electron gas interacts with the nuclear spins via $H \propto IS$ polarizing the nuclei while experiencing spin relaxation itself. It has been calculated that $\tau_{HF} \propto \sqrt{E_F}$. This means that hyperfine interactions are particularly important at low carrier densities.

In a confined system like a ballistic quantum dot, the first two mechanisms, which rely on extended motion of the electrons, should be of minor importance, while the hyperfine interaction remains relevant. This is an important factor and the reason why extremely long spin relaxation times can be observed in such systems.

21. Explain hyperfine interaction. Where does it take place and what is its importance in spin systems? In what devices could it be most efficient? What are possible applications of hyperfine interaction?

http://naturedocumentaries.org/3964/inner-life-cell/
Recent developments

• Magnetic semiconductors (quick performance)

• Spin injection
  • from a metallic ferromagnet into a semiconductor
  • from a magnetic semiconductor to a non-magnetic semiconductor

• Magnetic switching induced by spin currents

The discovery of GMR opened the door to a new field of science, magnetoelectronics (or spintronics), where two fundamental properties of the electron, namely its charge and its spin, are manipulated simultaneously.

Emerging nanotechnology was an original prerequisite for the discovery of GMR, now magnetoelectronics is in its turn a driving force for new applications of nanotechnology.

22. Name few modern spintronics trends and explain their importance. Do you aware of spintronics aspects in graphene and topological insulators (TIs)? Is single molecule GMR possible?
Recent STM developments

Atom-by-atom engineering and magnetometry of tailored nanomagnets

Roland Wiesendanger et al., Institute of Applied Physics, Hamburg University, Jungiusstrasse 11, D-20355 Hamburg, Germany

Experiments were performed in an ultra-high vacuum scanning tunnelling microscope at a temperature of T 0.3 K with a magnetic field B up to 12 T applied perpendicular to the sample surface. Spin-polarized Fe atoms on Cu.

https://www.youtube.com/watch?v=UVuW3fgTCTE
Spintronics (abbreviation for “Spin Transport Electronics”) is an emerging technology exploiting both the intrinsic spin of the electron and its associated magnetic moment, in addition to its fundamental electronic charge, in solid-state devices.

**New ingredients**

1. current-induced torque (CIT), also known as the spin-transfer torque. The manipulation of magnetization by CITs has its origin in angular momentum conservation, which twists the layer receiving the angular momentum carried by the spin current.

Spin is a key element for the next-generation magnetic random access memories, logic-in-memory architectures, and high-density memory devices.

Spin-torque-based nano-oscillators can be exploited as tunable microwave generators in wireless device technology, as well as a means of low-power spin-wave interconnects in logic devices.
2. The second is the spin Hall effect (SHE), which originates from the relativistic spin-orbit coupling (SOC) interaction that turns the electrons perpendicular to the current in a spin-dependent way.

Despite the short time since its discovery, SHE has now become a standard tool in the detection of spin currents and spin polarization. It has been used to create one of the first spin field-effect transistors (FETs), to measure spin currents generated by magnetization dynamics, and even to generate spin currents large enough to produce spin-torque effects.

3. The third subfield is spin caloritronics. Envisaged in an early work on spin injection and ignited by the discovery of the spin Seebeck effect, thermal gradients driving heat currents are now being exploited to generate spin currents. The origin of the effect seems to be the coupling between collective spin modes (magnons) and lattice excitations (phonons).

The spin dependence of the heat conductance, Seebeck and Peltier effect may have important energy applications.
4. The fourth is silicon spintronics. Silicon is not only abundant (its oxide is sand) and the central material for electronics, but it also has very desirable long spin-relaxation times.

It was a late bloomer in spintronics, mostly because its indirect band gap and weak SOC have, for decades, precluded spin injection and detection.

Recent experimental breakthroughs have, however, demonstrated that the electron spin in silicon can be reliably injected and detected as well as transferred over relatively large distances, allowing a seamless integration with electronic circuits, such as connecting close-by processor cores.

5. Finally, the fifth entails the spintronic aspects of graphene and topological insulators (TIs), which originate from the band-structure properties and create an effective topological knot. This property protects the states of graphene or the surface states of a TI from non-magnetic disorder effects.
A ferromagnetic emitter to inject spin-polarized electrons via a tunnel barrier into a silicon base.

These spin-polarized minority carriers traverse the base diffusively and are harvested by the ferromagnetic collector via another tunnel barrier.

The spin selectivity derives from the back-biased collector presenting a different density of final spin states to the spin-polarized minority carriers in the base.

Figure 1. (a) Schematic of the modelled device where the emitter-base injector is a forward biased n–p junction. (b) Schematic of the fabricated spin transistor with silicon base.

Spintronics
GMR through a single molecule

H$_2$Pc (hydrogen phthalocyanine) molecules adsorbed onto two Co islands on the Cu(111) surface.

Co(111) tip

Co(111) substrate

Magnetoresistance 51%

Schmaus et al., cond-mat 2011
Quantum devices (qubits and gates)

Having nanosecond resolution one have to use a lot of high frequency components, which must all work at 40 millikelvin.

Here is a picture of a board with a sample on it. There is a microwave stripline for four coaxial cables to bring high frequency signals to the sample.

23. In what quantum devices could spin be used? Can it be relevant to quantum computing? What are other emerging applications of spintronics? What problems need to be solved in this area?
Electronics applications

Read head of hard disc drive

1997 (before GMR): 1 Gbit/in², 2007: GMR heads ~ 300 Gbit/in²

Current pulse drives domain wall bit sequence through racetrack

Magnetic memories

Spintronics
Spin injection in semiconductor – optimizing interfaces and materials are needed.
- one of ways – using magnetic semiconductors as FM decreases impedance mismatch
• Gate-induced spin rotation (Rashba effect)
• Spin relaxation and decoherence

Spintronics is a new emerging field providing promising solutions for signal processing and realization of computer algorithms.
Spin depolarization is still large – many things have to be done to make coherent spintronics practical.