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Introduction to spin physics in semiconductors

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Abstract

This lecture presents a brief survey of spin physics in semiconductors together with the historic roots of the recent activity in researching spin-related phenomena.

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1. Introduction: historical background

Probably the first step towards today's activity was made by Robert Wood in 1923/24 when even the notion of electron spin was not yet introduced. In a charming paper [1] Wood and Ellett describe how the initially observed high degree of polarization of mercury vapor fluorescence (resonantly excited by polarized light) was found to diminish significantly in later experiments. "It was then observed that the apparatus was oriented in a different direction from that which obtained in earlier work, and on turning the table on which everything was mounted through ninety degrees, bringing the observation direction East and West, we at once obtained a much higher value of the polarization." In this way Wood and Ellett discovered what we now know as the Hanle effect, i.e. depolarization of luminescence by transverse magnetic field (the Earth's field in their case). It was Hanle who carried out detailed studies of this phenomenon and provided the physical interpretation [2].

The subject did not receive much attention until 1949 when Brossel and Kastler [3] initiated profound studies of optical pumping in atoms, which were conducted by Kastler and his school in Paris in the 50ies and 60ies. (See Kastler's Nobel Prize award lecture. [4]) The basic physical ideas and the experimental technique of today's "spintronic" research originate from these seminal papers: creation of a non-equilibrium distribution of atomic angular moments by optical excitation, manipulating

this distribution by applying dc or ac fields, and detecting the result by studying the luminescence polarization. The relaxation times for the decay of atomic angular moments can be quite long, especially when hyperfine splitting due to the nuclear spin is involved. A number of important applications have emerged from these studies, such as gyroscopes and hypersensitive magnetometers, but in my opinion, the knowledge obtained is even more valuable. The detailed understanding of various atomic processes and of many aspects of interaction between light and matter was pertinent to the future developments, e.g. for laser physics.

The first experiment on optical spin orientation of electrons in a semiconductor (Si) was done by Georges Lampel [5] in 1968, as a direct application of the ideas of optical pumping in atomic physics. The important difference is that now these are the free conduction band electrons that get spin-polarized, rather than electrons bound in an atom. This pioneering work was followed by extensive experimental and theoretical studies mostly performed by small research groups at Ecole Polytechnique in Paris and at Ioffe Institute in St Petersburg (Leningrad) in the 70ies and early 80ies. It is interesting that at the time this research met with almost total indifference by the rest of the physics community.

2. Interactions involving spin

The existence of an electron spin, $s=1/2$, and the associated magnetic moment of the electron, $\mu=e\hbar/2mc$, has many

consequences, some of which are very important and define the very structure of our world, while others are more subtle, but still quite interesting.

2.1. Exchange interaction. In fact, this is the result of Coulomb interaction between electrons, which becomes spin-dependent because of the requirement that the wavefunction of a pair of electrons be anti-symmetric with respect to the interchange of electron coordinates and spins. If the electron spins are parallel, the coordinate part of the wavefunction should be antisymmetric: $\psi_{\uparrow\uparrow}(\mathbf{r}_2, \mathbf{r}_1) = -\psi_{\uparrow\uparrow}(\mathbf{r}_1, \mathbf{r}_2)$, which means that the probability that two electrons are very close to each other is small compared to the opposite case, when the spins are antiparallel and accordingly their coordinate wavefunction is symmetric. Electrons with parallel spins are then better separated in space, so that their repulsion is less and consequently the energy of parallel spins is lower.

2.2. Spin-orbit interaction. If an observer moves with a velocity \mathbf{v} in an external electric field \mathbf{E} , he will see a magnetic field $\mathbf{B} = (1/c)\mathbf{v}\wedge\mathbf{E}$, where c is the speed of light (Gaussian units are used everywhere in this lecture). Thus, when an electron follows its orbit in the electric field produced by the nucleus of an atom, this magnetic field appears in the electron's reference frame. Being perpendicular both to \mathbf{E} and \mathbf{v} , \mathbf{B} is normal to the plane of the orbit, thus it is parallel to the orbital angular momentum \mathbf{L} . This magnetic field acts on the electron magnetic moment, giving an energy $\pm \mu B$, depending on the orientation

of the electron spin (and hence its magnetic moment) with respect to \mathbf{B} (or to \mathbf{L}).

This is the physical origin of the spin-orbit interaction, which can be written as $A(\mathbf{L}\mathbf{S})$, the constant A depending on the electron state in an atom. This interaction results in splitting of atomic levels (the *fine structure*), which strongly increases for heavy atoms (large Z). The reason is that there is a certain probability for the electron to approach the nucleus and thus to see the very strong electric field produced by the unscreened nuclear charge $+Ze$ at the center.

In semiconductors, the spin-orbit interaction depends not only on the velocity of the electron (or its quasi-momentum), but also on the structure of the Bloch functions defining the motion on the atomic scale.

Spin-orbit interaction is key to our discussion as it enables optical spin orientation and detection (the electrical field of the light wave does not interact directly with the electron spin). It is (in most cases) responsible for spin relaxation. And finally, it makes the transport and spin phenomena inter-dependent.

2.3. Hyperfine interaction with nuclear spins. This is the magnetic interaction between the electron and nuclear spins, which may be quite important if the lattice nuclei in a semiconductor have non-zero spin (like in GaAs). If the nuclei get polarized, this interaction is equivalent to the existence of effective nuclear magnetic field acting on electron spins. The effective field of 100% polarized nuclei in GaAs would be several Tesla! Experimentally, nuclear polarization of several percent is easily achieved.

2.4. Direct magnetic interaction.

This is the dipole-dipole interaction between the magnetic moments of a pair of electrons. This interaction is normally too weak to be of any importance in semiconductors.

3. Optical spin orientation and detection.

In cubic semiconductors like GaAs the conduction band originates from an atomic s -state, while the valence band originates from a p -state. Because of the spin-orbit interaction the valence band is split into bands of light and heavy holes (corresponding to atomic states with $j=3/2$) and the split-off band ($j=1/2$). When a right circularly polarized photon is absorbed during an interband transition, its angular momentum (+1) is distributed between the photoexcited electron and hole according to the selection rules determined by the band structure of the semiconductor. It can be shown that if we take the average over the directions of momenta of the photoexcited carriers, the result is the same as in optical transitions between atomic states with $j=3/2$, $m_j = -3/2, -1/2, +1/2, +3/2$ (corresponding to bands of light and heavy holes) and $j=1/2$, $m_j = -1/2, +1/2$ (corresponding to the conduction band).

This means that absorption produces an average electron spin (projection on the direction of excitation) equal to $(-1/2)(3/4) + (+1/2)(1/4) = -1/4$ and an average hole spin equal to $+5/4$, with a sum +1, equal to the angular momentum of the absorbed right circularly polarized photon. Thus in a p -type semiconductor the degree of spin polarization of the photoexcited electrons

will be -50%, the minus sign indicating that the spin orientation is opposite to the angular momentum of incident photons.

If our electron immediately recombines with its partner hole, a 100% circularly polarized photon will be emitted. However in a p -type semiconductor electrons will predominantly recombine with the majority holes, which are not polarized. Then the same selection rules show that the circular polarization of luminescence should be $P_0 = 25\%$, if the holes are not polarized, and if no electron spin relaxation occurs during the electron lifetime τ , i.e. if $\tau_s \gg \tau$. Generally, the degree P of circular polarization of the luminescence excited by circular polarized light is less than P_0 :

$$P = \frac{P_0}{1 + \frac{\tau}{\tau_s}}$$

In an optical spin orientation experiment a semiconductor (usually p -type) is excited by circularly polarized light with $\hbar\omega > E_g$. The circular polarization of the luminescence is analyzed, which gives a direct measure of the electron spin polarization. Thus various spin interactions can be studied by simple experimental means. The condition $\tau_s > \tau$ can often be achieved even at room temperature.

4. The Hanle effect

Depolarization of luminescence by a transverse magnetic field is effectively employed in experiments on spin orientation in semiconductors. This effect is due to the precession of electron spins in a magnetic field \mathbf{B} with the Larmor frequency Ω .

This precession, along with spin pumping, spin relaxation, and recombination is described by the following simple equation of motion of the average spin vector \mathbf{S} :

$$\frac{d\mathbf{S}}{dt} = \boldsymbol{\Omega} \wedge \mathbf{S} - \frac{\mathbf{S}}{\tau_s} - \frac{\mathbf{S} - \mathbf{S}_0}{\tau},$$

where the first term in the rhs describes spin precession in magnetic field ($\boldsymbol{\Omega} = \mu g \mathbf{B} / \hbar$), the second term describes spin relaxation, and the third one describes generation of spin by optical excitation and recombination. The vector \mathbf{S}_0 is directed along the exciting light beam, its absolute value is equal to the initial average spin of photo-created electrons.

In the stationary state ($d\mathbf{S}/dt=0$) and in the absence of magnetic field, one finds:

$$S_z(0) = \frac{S_0}{1 + \frac{\tau}{\tau_s}},$$

where $S_z(0)$ is the projection of the spin on the direction of \mathbf{S}_0 (z -axis). Since $S_z(0)$ is equal to the degree of polarization of the luminescence, this formula is equivalent to the above expression for P . In presence of magnetic field transverse to \mathbf{S}_0 we obtain:

$$S_z(B) = \frac{S_z(0)}{1 + (\Omega \tau^*)^2}, \quad \text{where} \quad \frac{1}{\tau^*} = \frac{1}{\tau} + \frac{1}{\tau_s}.$$

The effective time τ^* defines the width of the depolarization curve. Thus the spin projection S_z (and hence the degree of circular polarization of the luminescence) decreases as a function of the transverse magnetic field. Combining the measurements of the zero-field value $P = S_z(0)$ and of the magnetic field dependence in the Hanle effect, we can find the two

essential parameters: electron lifetime τ and the spin relaxation time τ_s under steady-state conditions.

If polarized electrons are created by a short pulse, time-resolved measurements of the degree of circular polarization of the luminescence reveal, very impressively, the damped spin precession around the direction of magnetic field [7].

5. Spin relaxation

Spin relaxation, i.e. disappearance of initial non-equilibrium spin polarization, is the central issue for all spin phenomena. Spin relaxation can be generally understood as is a result of the action of fluctuating in time magnetic fields. In most cases, these are not “real” magnetic fields, but rather “effective” magnetic fields originating from the spin-orbit, or, sometimes, exchange interactions.

5.1. Generalities. A randomly fluctuating magnetic field is characterized by two important parameters: its amplitude (or, more precisely, its rms value), and its correlation time τ_c , i.e. the time during which the field may be roughly considered as constant. Instead of the amplitude, it is convenient to use the average precession frequency in this random field, ω .

The spin makes a precession around the (random) direction of the effective magnetic field with a typical frequency ω and during a typical time τ_c . After a time τ_c the direction and the absolute value of the field change randomly, and the spin start its precession around the new direction of the

field. After a certain number of such steps the initial spin direction will be completely forgotten.

What happens depends on the value of the dimensionless parameter $\omega\tau_c$, which is the typical angle of spin precession during the correlation time. Two limiting cases may be considered:

a) $\omega\tau_c \ll 1$ (most frequent case). The precession angle is small, so that the spin vector experiences a slow angular diffusion. During a time t , the number of random steps is t/τ_c , for each step the squared precession angle is $(\omega\tau_c)^2$. These steps are not correlated, so that the total squared angle after time t is $(t/\tau_c)(\omega\tau_c)^2$. The spin relaxation time τ_s may be defined as the time at which this angle becomes of the order of 1. Hence:

$$\frac{1}{\tau_s} \sim \omega^2 \tau_c.$$

This is essentially a *classical* formula (the Planck constant does not enter), although certainly it can be also derived quantum-mechanically. Note, that $\tau_s \gg \tau_c$.

b) $\omega\tau_c \gg 1$. This means that during the correlation time the spin will make many rotations around the direction of the magnetic field. During the time on the order of $1/\omega$ the spin projection transverse to the random magnetic field is (on the average) completely destroyed, while its projection along the direction of the field is conserved. After time τ_c the magnetic field changes its direction, and the initial spin polarization will be disappear. Thus for this case $\tau_s \sim \tau_c$.

This consideration is quite general and applies to any mechanism of spin

relaxation. We have only to understand the values of the relevant parameters ω and τ_c for a given mechanism.

5.2. Some spin relaxation mechanisms

- *Relaxation by phonons.* The electrical field, accompanying lattice vibrations, is transformed to an effective magnetic field through spin-orbit interaction. This mechanism is normally rather weak.

- *Relaxation in scattering by charged impurities (Elliott-Yafet mechanism).* Here again the impurity electric field transforms into a magnetic field through spin-orbit interaction. The relaxation rate is obviously proportional to the impurity concentration.

- *Dyakonov-Perel mechanism.* This one is related to spin-orbit splitting of the conduction band in non-centrosymmetric semiconductors, like GaAs (but not Si or Ge, which are centrosymmetric). The spin-dependent energy, as first pointed out by Dresselhaus, should be written in the form:

$$E(\mathbf{p}) = \frac{p^2}{2m_c} + \hbar \boldsymbol{\Omega}(\mathbf{p}) \cdot \mathbf{S},$$

where the additional term can be viewed as energy of a spin in an effective magnetic field. Here $\boldsymbol{\Omega}(\mathbf{p})$ is a vector depending on orientation of the electron momentum with respect to the crystal axes. For a given \mathbf{p} , $\boldsymbol{\Omega}(\mathbf{p})$ is the spin precession frequency in this field. This frequency is proportional to $p^3 \sim E^{3/2}$. The effective magnetic field changes in time because the direction of \mathbf{p} varies due to electron collisions. Thus the correlation time τ_c is on the order of the momentum relaxation time τ_p , and if $\boldsymbol{\Omega} \tau_p$ is small, which is normally the case, we get:

$$\frac{1}{\tau_s} \sim \Omega^2 \tau_p.$$

In contrast to the Elliott-Yafet mechanism, now the spin relaxation rate increases when the impurity concentration decreases (i.e. when τ_p becomes longer). It happens that this mechanism is often the dominant one, both in bulk A^{III}B^V semiconductors, like GaAs and in 2D structures (where $\Omega(\mathbf{p}) \sim p$).

- *Bir-Aronov-Pikus mechanism.* This is a mechanism of spin relaxation of non-equilibrium electrons in *p*-type semiconductors due to the exchange interaction between the electron and hole spins. The spin relaxation rate being proportional to the number of holes, this mechanism may become the dominant one in heavily *p*-doped semiconductors.

- *Relaxation via hyperfine interaction with nuclear spins.* The electron spin interacts with the spins of the lattice nuclei (see below), which are normally in a disordered state. Thus the nuclei provide a random effective magnetic field, acting on the electron spin. The corresponding relaxation rate is rather weak, but may become important for localized electrons, when other mechanisms, associated with electron motion, do not work.

- *Spin relaxation of holes in the valence band.* The origin of this relaxation is in the spin-orbit interaction, which leads to the splitting of the valence band into subbands of light and heavy holes. In this case $\hbar \Omega(\mathbf{p})$ is equal to the energy difference between light and heavy holes for a given \mathbf{p} and the correlation time is again τ_p . However, in contrast to the situation for electrons in the conduction band, we have

now the opposite limiting case: $\Omega \tau_p \gg 1$. So, the hole spin relaxation time is on the order of τ_p , which is very short. One can say that the hole “spin” \mathbf{J} is rigidly fixed with respect to its momentum \mathbf{p} , and because of this, momentum relaxation leads automatically to spin relaxation. For this reason, normally it is virtually impossible to maintain an appreciable non-equilibrium polarization of holes.

6. Spin transport phenomena

Some interesting effects are related to the difference of Fermi levels for spin-up and spin-down electrons, if a non-equilibrium spin polarization is achieved in a degenerate electron gas.

Other transport phenomena predicted in Refs. [8,9] are due to spin-orbit interaction. They are described by the following phenomenological equations:

$$\frac{\partial S_\beta}{\partial t} + \frac{\partial q_{\alpha\beta}}{\partial x_\alpha} + (\mathbf{\Omega} \wedge \mathbf{S})_\beta + \frac{S_\beta}{\tau_s} = 0$$

$$q_{\alpha\beta} = -D_s \frac{\partial S_\beta}{\partial x_\alpha} + \beta_s n \varepsilon_{\alpha\beta\gamma} E_\gamma$$

$$\mathbf{q} = -\beta n \mathbf{E} \wedge \mathbf{S} - \delta \text{curl } \mathbf{S},$$

where the spin flow (or spin current) tensor $q_{\alpha\beta}$, introduced in [7,8], gives the flow density of the β spin component in the direction α , \mathbf{E} is the electric field, \mathbf{S} is the spin density, n is the electron concentration, and \mathbf{q} is the electron flow density ($\mathbf{q} = \mathbf{j}/e$).

The coefficients β , β_s , and δ are proportional to the spin-orbit interaction. The term with $\mathbf{E} \wedge \mathbf{S}$ is responsible for the so-called anomalous Hall effect, which is well known.

The new phenomena, described by the terms with β_s and δ are: 1) The appearance of spin current in the direction perpendicular to the electric field leading to spin accumulation near the surface (now called Spin Hall effect) and 2) the existence of an electrical current related to a spin density, which varies in space and proportional to curl \mathbf{S} . The second effect was observed a long time ago [10,11], while the first one was experimentally found only recently [12,13]. A combined action of the two effects should lead to a small change in the sample resistance in a magnetic field parallel to the electric current. (not yet observed experimentally).

A microscopic theory is needed to evaluate the coefficients in the phenomenological equations above. The coupling between electric and spin currents can arise [9] because of spin asymmetry in scattering caused by spin-orbit interaction (the Mott effect). A theory describing this coupling for holes in the valence band was developed in Ref. 14.

Recently, it was claimed that an “intrinsic” spin current in electric field should exist, which is not due to the Mott effect, but rather to spin-orbit Bychkov-Rashba band splitting. It was shown in a number of works (e.g. [15]), that in fact the “intrinsic” effect does not exist, and this is what I think too.

8. The electron-nuclear spin system

In GaAs all the lattice nuclei have spin. The non-equilibrium spin-oriented electrons can easily transmit their polarization to the nuclei, thus creating an effective magnetic field, acting back on the electron spin (but not on its orbital motion). This field can strongly influence the electron polarization, for example, via the Hanle effect. Thus the spin-oriented electrons and the polarized lattice nuclei form a strongly coupled system, in which spectacular non-linear phenomena, like self-sustained slow oscillations and hysteresis are observed by simply looking at the circular polarization of the luminescence.

The physics of these phenomena are governed by three basic interactions:

a) *Hyperfine interaction between electron and nuclear spins.* The interaction has the form $A\mathbf{I}\mathbf{S}$, where \mathbf{I} is the nuclear spin and \mathbf{S} is the electron spin. If the electrons are in equilibrium this interaction provides a mechanism for nuclear spin relaxation, if the electron spin system is out of equilibrium, it leads to *dynamic nuclear polarization*. These processes are very slow (from seconds to minutes, to hours), compared to the characteristic electron time scale. On the other hand, if the nuclei are polarized this interaction is equivalent to the existence of an *effective nuclear magnetic field*. The field of 100% polarized nuclei in GaAs would be about 7T! Experimentally, nuclear polarization of several percent is easily achieved.

b) *Dipole-dipole interaction between nuclear spins.* This interaction can be characterized by the *local magnetic field*, B_L , on the order of several Gauss, which is created at a given nuclear site by the

neighboring nuclei. The precession period of a nuclear spin in the local field, on the order of $\tau_N \sim 10^{-4}$ s, gives a typical time scale for the nuclear spin system. During this time thermal equilibrium within this system is established, with a *nuclear spin temperature*, which may be very different from the crystal temperature, for example, something like 10^{-6} K. The dipole-dipole interaction is also responsible for the *nuclear spin diffusion* – a process that tends to make the nuclear polarization uniform in space. The nuclear spin diffusion coefficient can be estimated as $D_N \sim a^2/\tau_N \sim 10^{-12}$ cm²/s, where a is the distance between the neighboring nuclei. Thus it takes about 1s to spread out the nuclear polarization on a distance of 100 Å, and several hours for a distance of 1 micron.

c) *Zeeman interaction* of electron and nuclear spins with the external magnetic field.

The interplay of these interactions under various experimental conditions accounts for the extremely rich and interesting experimental findings in this domain [16-18].

One prediction that we have made 34 years ago, the dynamic nuclear self-polarization [19,20] is still waiting for being discovered. Namely, below a certain critical temperature, a large spontaneous nuclear polarization should appear in a small applied magnetic field if the electron spins are maintained in an *unpolarized* state.

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