Optica Applicata, Vol. XXXVI, No. 2–3, 2006

Electrically detected spin resonance

JACEK BŁONIARZ, ZBYSŁAW WILAMOWSKI

Institute of Physics Polish Academy of Sciences, al. Lotników 32/46, 02-668 Warsaw, Poland

Corresponding author: Z. Wilamowski, wilamz@ifpan.edu.pl

An amplitude and a line shape of electrically detected signal of spin resonance are discussed. Since the signal scales with changes of spin polarization under resonance condition it is proportional to longitudinal spin relaxation. The analysis shows that such a method of detection of spin resonance is especially useful for low dimensional semiconductor structures.

Keywords: spin resonance, spin-orbit coupling, spin relaxation.

1. Introduction

Electron spin resonance (ESR) is a powerful experimental technique which allows studying details of spin properties. Nowadays, it becomes even more important because of a possible application in spin electronics. ESR is used not only for detail investigation of spin properties, but also for an effective spin manipulation. In particular, strong pulses of microwaves, as used in spin echo experiments, allow for a controlled spin rotation.

Classical ESR is measured in a microwave cavity. The applied frequency range is between a few and a few hundred GHz. In commercial ESR spectrometer, ESR signal is measured by monitoring the microwave power absorbed in microwave cavity. For that purpose a kind of microwave bridge is usually used. Sample is located in a maximum of magnetic microwave field and the resonance absorption is caused by magnetic dipole transition.

Unfortunately, the classical ESR cannot be applied to low dimensional nano structures. The main reason is the lack of sensitivity. Typical sensitivity of commercial spectrometers is of the order of 10^{10} spins at room temperature and increases with temperature lowering. This is a very sensitive method for volume samples. When sample volume is of the order of few cubic millimeters, ESR allows detection of very low concentration of magnetic centers, smaller than 10^9 spins. For low dimensional structure, however, when the sample volume is very small the applicability of classical ESR becomes strongly limited. In such cases, the electrically detected spin resonance (EDSR) becomes of crucial importance [2, 3]. Also, in high frequency spin resonance the application of EDSR becomes very useful. In the millimeter range of microwaves there is a technical difficulty in building a high quality microwave cavity and in controlling the balance of a microwave bridge which is needed for a precise measurement of microwave absorption. Since in EDSR the usage of microwave cavity is not a crucial point, it is simply easier to perform an experiment in this technique.

2. Idea of EDSR

The main idea behind electrical detection is based on the dependence of electric conductivity σ on spin polarization η. Usually, the mechanism of the dependence $\sigma(\eta)$ is not well explained but theoretical consideration indicates that this is a complex consequence of spin-orbit coupling [1, 4]. Since $\sigma(\eta)$ is an even function, for low η, it can be parameterized by a single parameter δ [3]:

$$\sigma(\eta) = \sigma_0\left(1 + \delta\eta^2 + \ldots\right) = \sigma_0\left(1 + \delta\eta_0^2\right) + 2\sigma_0\delta\left(\eta - \eta_0\right) \tag{1}$$

Under resonance condition, due to microwave absorption, the spin polarization decreases. It is a function $\eta(H, P)$ of applied magnetic field H and microwave power P. Consequently, a measurement of electric conductivity $\sigma(H, P)$ allows spin resonance to be observed.

In principle, two different methods of conductivity measurement can be distinguished: contact [2] and contactless [3] methods. The former requires metallic wires to be inserted into microwave cavity and a dc or low frequency conductivity is then measured. Wires perturb microwaves in the cavity, but when they are very close to each other, and are oriented perpendicularly to electric microwave field, the quality of microwave cavity is only weakly perturbed.

In the contactless method, a sample is inserted into a microwave cavity and the electric conductivity changes under spin resonance condition are monitored via microwave absorption. The microwave absorption is proportional to the square of the electric field at the sample and to ac electric conductivity σ_ω. Therefore, in general, the ESR absorption measured by a standard spectrometer is a sum of two signals, *i.e.*, that of classical magnetic dipole absorption proportional to imaginary part of magnetic susceptibility $\chi''(\omega, H)$ and that of electric absorption proportional to microwave conductivity $\sigma_\omega(H, P)$. The second contribution to the absorption signal is negligible for insulating samples, but it can be dominant for semiconductors and metals. For example, for high mobility 2D electron gas the background electric absorption due to σ_0 is by 8 orders of magnitude higher than the spin resonance signal. In such a case, even a very weak dependence of electric conductivity on spin polarization $\sigma(\eta)$ (small value of parameter δ in Eq. (1)) can lead to a strong electric ESR signal.

Summing up, the contact method of electrical detection can be applied to real nano structure systems. The sensitivity of this method is independent of sample volume. In the case of the contactless method, the signal is proportional to the total electric absorption; therefore it is proportional to sample volume. For highly conducting samples, *e.g.*, metallic layers, a conducting channel in FET or for two dimensional electron gas, the electric microwave absorption is by many orders of magnitude higher than the magnetic dipole absorption. Therefore, relatively small changes in electric absorption which may occur under spin resonance conditions can overcome magnetic dipole absorption. In other words, the contactless EDSR signal can overcome the classical ESR signal.

3. Stimulation of ESR: magnetic and electric dipole transitions

In the case of ESR of conducting electrons as well as in the case of EDSR of local spins (where spin polarization of carriers is ruled by spin polarization of local spins via carrier-local spin exchange interaction), the dependence of electric conductivity on spin polarization (see Eq. (1)) is a consequence of spin orbit coupling. Such a coupling, however, leads simultaneously to a finite electric dipole transition between spin levels [5, 6]. Therefore, when symmetry conditions are fulfilled (lack of inversion symmetry) and the spin orbit coupling in carrier band structure cannot be neglected, the spin flip transition of effective mass carrier and effective mass shallow impurity states can be stimulated not only by magnetic dipole, but also by electric dipole transition [5]. The probability of magnetic dipole transition are ruled by matrix element of spin operator between the spin states and weakly depends on an actual case. In particular, the matrix element is equal for all spins. In contrast, the probability of electric dipole transition can exceed the probability of magnetic dipole transition by orders of magnitude, *e.g.*, for ESR of carriers in CdSe [6], it can be of a similar order of magnitude as in ESR of shallow donor in ZnO [7] or in 2D electron gas in Si/SiGe quantum wells. Finally, electric dipole transition can be weak or strictly forbidden whenever the system is characterized by inversion symmetry.

Generally, two different contributions to the transition probability should be considered. These contributions can be distinguished when the angular dependence of the ESR signal amplitude is investigated. The magnetic dipole transition is almost isotropic. Only the g-factor anisotropy can lead to the amplitude anisotropy, while the electric dipole transition is strongly anisotropic and vanishes for specific directions of the applied field.

4. Shape of electrically detected spin resonance

In a steady-state of magnetic resonance condition (slow passage condition) the spin polarization $\eta(\omega, H, H_1)$ results from the balance of microwave absorption, proportional to both the imaginary part of magnetic susceptibility $\chi''(\omega, H, H_1)$, and the magnetization relaxation rate $1/T_1$. The resulting value can also be found from the proportionality $\eta(\omega, H, H_1) \propto \chi''(\omega, H, H_1)$, which leads to the expression [3]:

$$\eta(h, p) = \eta_0 \frac{1 + h^2}{1 + p + h^2} \tag{2}$$

Here, $h = \gamma(H - H_0)/\Delta\omega$ is the normalized dimensionless magnetic field and $p = \gamma^2 H_1^2 T_1/\Delta\omega$ is dimensionless microwave power. Parameter γ is a gyroscopic factor, $\Delta\omega = \gamma\Delta H = 1/2T_1 + 1/T_2$ is the resonance linewidth, H_1 is the amplitude of microwave field, T_1 and T_2 are longitudinal and transverse spin relaxation times, respectively.

Comparison of Eqs. (1) and (2) leads to the expression for line shape of electrically detected spin resonance, *i.e.*, to dependence of electric conductivity on magnetic field and microwave power

$$\sigma(h,p) - \sigma_0 \cong -\delta\left[\eta^2(h,p) - \eta_0^2\right] = -2p\delta\eta_0^2 \frac{2 + p + 2h^2}{2\left(1 + p + h^2\right)^2}$$

For low microwave power ($p \ll 1$) the shape of resonance line is described by the Lorentzian function $\sigma(h,p) - \sigma_0 \cong -2p\delta\eta_0^2 \dfrac{1}{1 + h^2}$. Consequently, the electrically detected and classical magnetic dipole spin resonance are characterized by the same resonance line but their amplitudes are characterized by a different dependence on microwave power. Classical ESR is proportional to $\chi''(\omega, H, H_1)$ which is power independent in a low power limit, while EDSR is proportional to p in that power range. When the classical ESR is measured by monitoring the power absorbed in microwave cavity, then the ESR signal is proportional to $p^{1/2}$. The change of electric conductivity at spin resonance scales with p while contacless signal of the EDSR is proportional to $p^{3/2}$. Different dependence of the amplitudes of a classical magnetic dipole and EDSR on microwave power allows us to distinguish these two contributions to spin resonance.

Because of a strong dependence of EDSR on microwave power the EDSR measurements usually require a strong microwave power. In such a limit, however, one has to consider the change of line shape caused by saturation of changes of spin polarization. In high power range ($p \gg 1$) all signal amplitudes saturate, the line-shape functions are not anymore characterized by the Lorentzian shape and their linewidths increase. For all cases they increase with $p^{1/2}$ but the peak-to-peak linewidth of EDSR is higher by a factor of $3^{1/2}$ as compared to the classical case.

5. Conclusions

In metals, the process of microwave absorption is additionally complicated by the fact that the spin diffusion length can be greater than the skin depth. As was shown in the classical paper by Dyson, the magnetic dipole absorption in metals leads to an asymmetric (Dysonian) line shape. The Dysonian shape of the absorption line at spin resonance in a conducting sample originates from the fact that due to spin diffusion the precession phase of magnetization within the skin depth is shifted as compared to the magnetic component of microwave. Because the measurement of EDSR reflects the change of spin polarization the shape of the resonance line is not affected by spin diffusion. On the other hand, the change of spin polarization in metals occurs in the vicinity of the metal surface only. The characteristic depth of modified spin polarization is limited by both the penetration of microwaves and the spin diffusion length. When these lengths are much smaller than the sample thickness, the sample conductivity is only weakly modified by change of spin polarization. It is for this reason that the applicability of EDSR to thick metallic layers is limited.

On the other hand, EDSR is a powerful resonance technique for low dimensional structures. The contactless method is useful for investigation of metallic 2D layer while the EDSR measured using contact method can also be applied to low-dimensional nano-elements. Moreover, EDSR can be easily used for high frequency spin resonance.

EDSR is of particular importance for systems characterized by long spin relaxation times, where spin polarization can be easily modified by microwave absorption.

Acknowledgements – This work was supported by KBN grant PBZ 044/P03/2001.

References

[1] Pudalov V.M., Gershenson M.E., Kojima H., Brunthaler G., Prinz A., Bauer G., *Interaction effects in conductivity of Si inversion layers at intermediate temperatures*, Physical Review Letters **91**(12), 2003, pp. 126403/1–4.

[2] Graeff C.F.O., Brandt M.S., Stutzmann M., Holzmann M., Abstreiter G., Schaffler F., *Electrically detected magnetic resonance of two-dimensional electron gases in Si/SiGe heterostructures*, Physical Review B: Condensed Matter **59**(20), 1999, pp. 13242–50.

[3] Wilamowski Z., Jantsch W., *Suppression of spin relaxation of conduction electrons by cyclotron motion*, Physical Review B: Condensed Matter and Materials Physics **69**(3), 2004, pp. 35328/1–10.

[4] Fedorych O.M., Wilamowski Z., Jantsch W., Sadowski J., *Electrically detected magnetic resonance*, Acta Physica Polonica A **105**(6), 2004, pp. 591–8.

[5] Rashba E.I., *Spin dynamics and spin transport*, Journal of Superconductivity **18**(2), 2005, pp. 137–44.

[6] Dobrowolska M., *Far-infrared spin resonance in narrow-gap semiconductors*, Semiconductor Science and Technology **5**(3S), 1990, pp. S159–S168.

[7] Michaluk E., Wilamowski Z., Błoniarz J., Mycielski A., *Electric-dipole spin resonance in wurtzite ZnO*, Optica Applicata **36**(2–3), 2006, pp. 291–6.

Received December 15, 2005