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EXCHANGE INTEGRALS IN $Hg_{0.95}Mn_{0.05}Se$ OBTAINED BY THE WAVE SHAPE ANALYSIS OF SHUBNIKOV-DE HAAS OSCILLATIONS*

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The Shubnikov-de Haas oscillations were measured in $Hg_{0.95}Mn_{0.05}Se$ at liquid helium temperatures, in magnetic fields up to 13 tesla. The analysis of the experimental data was performed by means of the wave shape method. The dependence of effective g-factor of the conduction electrons and difference Dingle temperature on magnetic field was determined. Non-zero difference Dingle temperature is a clear evidence of spin dependent scattering in this material. The sp–d exchange constants consistent with extracted spin splitting and difference Dingle temperature, $\alpha = -0.39 \pm 0.06$ eV, $\beta = 0.95 \pm 0.07$ eV, are in good agreement with the values obtained from magnetooptics.

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Magnetic properties of diluted magnetic semiconductor (DMS) $Hg_{1-x}Mn_xSe$ strongly influence the energy spectrum of band carriers. The origin of this effect is that the spins localized on manganese ions interact with the conduction electron spins through Heisenberg-type interaction. The strength of this interaction is characterized by two constants (exchange integrals), α and β for s–d and p–d type coupling, respectively [1]. The experimental determination of these parameters is possible either by intraband [2] and interband [3] magnetooptical transitions, and also by fitting Shubnikov-de Haas (SdH) oscillations [4-8]. In narrow gap semiconductors the separating out of contributions involving α and β is particularly difficult, because of mixed (s- and p-like) character of the band carrier wave function. All magnetotransport studies referenced above are based on a calculation of the Landau levels within the Pidgeon-Brown model, and followed the fit of the positions of intersections of the Fermi energy with the Landau levels to measured positions of SdH maxima.

The aim of the present work is to investigate feasibility of yet another method of extracting exchange constants from SdH effect. We use the standard wave shape analysis for investigations of the de Haas-van Alphen effect in metals [9] modified

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by us suitably for the case of SdH effect in DMS [10]. The analysis makes use of first three harmonics of SdH oscillations. We fit the wave shape to the observed traces, after removing a non-oscillatory background. We obtained in this way the amplitudes and phases, which serve then to construct the so-called *observables* [9], which depend functionally on such basic parameters of the material as: m^* — the conduction electron effective mass at the Fermi level, $T_{\rm D}$ — the Dingle temperature, $\delta T_{\rm D} = (T_{\rm D\uparrow} - T_{\rm D\downarrow})/2$ — difference Dingle temperature for spin up and spin down electrons, and $g_{\rm eff} = g_{\rm c} + H_{\rm ex}/H$ — effective g-factor (where $g_{\rm c}$ is the g-factor of band electrons in absence of magnetic ions, $H_{\rm ex}/H$ — contribution due to Heisenberg-type interaction of electrons with localized Mn magnetic moments). Of course, the information concerning *sp–d* exchange constants appears in $\delta T_{\rm D}$ because of nonvanishing spin dependent scattering and in $g_{\rm eff}$ via modifications of the spin splitting of the Landau levels.

As mentioned, because of the mixing of s- and p-like wave functions, characteristic of narrow gap semiconductors, both exchange constants α and β are involved in $H_{\rm ex}$, as well as in $\delta T_{\rm D}$.

The following functional dependencies can be derived:

$$H_{\rm ex} = (c_1\alpha + c_2\beta)\langle S_z\rangle/\mu_{\rm B}, \tag{1}$$

$$\delta T_{\rm D} \approx (c_3\alpha^2 + c_4\beta^2)\langle S_z\rangle^2 \frac{(3\pi^2 n)^{1/3} m^*}{2\pi^2 k_{\rm B}\hbar^2}, \tag{2}$$

where n is electron concentration, m^* — effective mass at the Fermi level, $\langle S_z\rangle$ — average spin of Mn, c_1, c_2, c_3, c_4 are coefficients describing the mixing of s- and p-wave functions, which can be calculated in given sample provided that the Fermi level is known. When $\langle S_z\rangle$ is known, for example from magnetization measurements, the remaining unknown quantities in Eqs. (1), (2) are α and β. This method of determination of the exchange constants is similar to that presented in [11], the difference being that we were now able to establish experimentally the full dependence of both $H_{\rm ex}$ and $\delta T_{\rm D}$ on magnetic field.

In order to check if the above procedure gives reliable results, we performed SdH experiments on $\rm Hg_{0.95}Mn_{0.05}Se$ sample in a computerized experimental setup, at liquid helium temperatures, in magnetic fields up to 13 tesla. Typically, about 7000 points per one magnetic field sweep were recorded. Then, the wave shape analysis was performed. We obtained the following material parameters: electron concentration 1.1×10^{17} cm^{-3}, $m^* = 0.030 \pm 0.005$. Results for $H_{\rm ex}$ and $\delta T_{\rm D}$ are presented in Fig. 1. A strong spin-dependent scattering is clearly demonstrated as an increase in the absolute value of $\delta T_{\rm D}$. Then, using the magnetization data from [12] we found possible simultaneous solutions of Eqs. (1) and (2) in the (α, β) plane (see Fig. 2). The intersection of both solutions gives us a graphical estimate of values of exchange constants α and β, and moreover the area of this intersection determines the accuracy of deduced exchange constants. The exchange constants determined from Fig. 2: $\alpha = -0.39 \pm 0.06$ eV, $\beta = 0.95 \pm 0.07$ eV. The values of exchange constants are close to those obtained from interband magnetooptical measurements $\alpha = -0.4 \pm 0.1$ eV, $\beta = 0.7 \pm 0.1$ eV [3]. This good agreement for the well-known case of $\rm Hg_{1-x}Mn_xSe$ leads us to the conclusion that the above analysis is quite precise and may be applied also to other DMS. In particular, we intend to apply it to $Hg_{1-x}Fe_xSe$ which is difficult to study by means of magnetooptical methods.

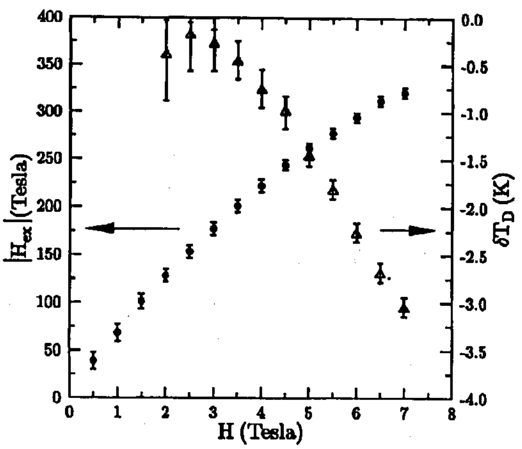

Fig. 1. Exchange contribution to conduction electron spin splitting (see Eq. (1)), and difference Dingle temperature as functions of magnetic field obtained by a wave shape analysis of SdH oscillations in $Hg_{0.95}Mn_{0.05}Se$ at 4.2 K.

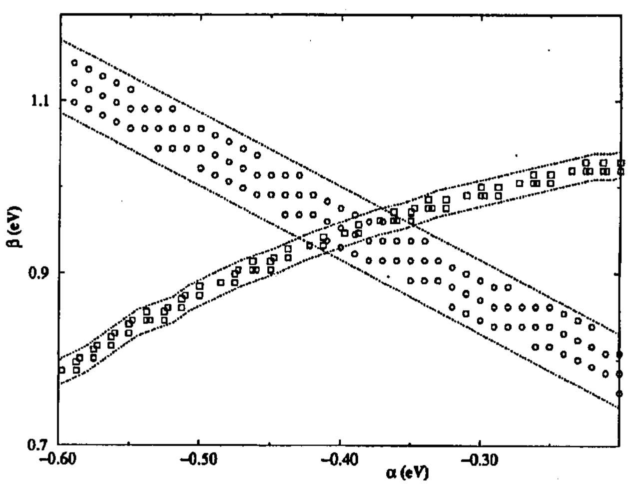

Fig. 2. Pairs of (α, β) corresponding to the best fit of Eq. (1) — circles, and Eq. (2) — squares. The intersection of two curves provides a simultaneous solution of both, and, thus determines final values of α and β.

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References

[1] J. Kossut, in: *Diluted Magnetic Semiconductors*, Eds. J.K. Furdyna, J. Kossut, *Semiconductors and Semimetals*, Vol. 25 Academic Press, Boston 1988, p. 183.

[2] K. Pastor, M. Jaczyński, J.K. Furdyna, *J. Phys. Soc. Jpn.* **49**, Suppl. A 779 (1980).

[3] M. Dobrowolska, W. Dobrowolski, R.R. Gałązka, A. Mycielski, *Phys. Status Solidi B* **105**, 447 (1981).

[4] S. Takeyama, R.R. Gałązka, *Phys. Status Solidi B* **96**, 413 (1979).

[5] P. Byszewski, M.Z. Cieplak, A. Mongrid-Górska, *J. Phys. C* **13**, 5383–91 (1980).

[6] H.M.A. Schleijpen, F.A.P. Bloom, *Phys. Status Solidi B* **135**, 605 (1986).

[7] J.A. Nobel, J.R. Anderson, W.B. Johnson, *Phys. Rev. B* **36**, 6012 (1987).

[8] W.B. Johnson, *J. Phys. Chem. Solids* **53**, 93 (1992).

[9] R.J. Higgins, D.H. Lowndes, in: *Electrons at the Fermi Surface*, Ed. M. Springford, Cambridge University Press, Cambridge 1980, p. 393.

[10] K. Dybko, J. Kossut, to be published.

[11] W. Lubczyński, J. Cisowski, J. Kossut, J.C. Portal, *Semicond. Sci. Technol.* **6**, 619 (1991).

[12] W. Dobrowolski, M.v. Ortenberg, A.M. Sandauer, R.R. Gałązka, A. Mycielski, R. Pauthenet, *Lecture Notes in Physics*, Eds. E. Gornik, H. Heinrich, L. Palmetshofer, Vol. 152, Springer Verlag, Berlin 1982, p. 302.