that the MTR measurements with circularly polarized light supply unambiguous and clearer information compared with TR with unpolarized light, both on the polarization state of the optical lines and on the exchange splitting of the electronic transitions. Measurements are in progress for extending the spectral range to the ultraviolet region and for studying the behavior of the MTR spectrum versus the temperature. Moreover, by a suitable best fit of the optical features of the spectrum it will be easier to follow the temperature dependence of the energy position and line shape in order to gain information about the dynamical spin fluctuation effect on the electronic state.

Also in order to determine in the case of the Eu chalcogenides the modulation mechanisms which affect the optical structures near T_c and their relative weights, MTR measurements at different temperatures are in progress on EuO.

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"Spin-Doping," a New Tool in Electronic Band Structure Investigation

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"Spin doping" by paramagnetic ions adds to the electronic g factor of charge carriers in semiconductors, a temperature sensitive part, so that by means of the artificial temperature dependence any intraband resonance transition can be identified unambiguously.

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Optical resonance spectroscopy is a powerful means for the investigation of the electronic energy-band structure of solids. Submillimeter magnetospectroscopy especially provides detailed information on the intraband energy separation of the Landau levels in the presence of an external magnetic field, assuming that the initial and final states of the resonance transition are unambiguously identified. This identification, however, is often somewhat arbitrary. For a more complicated band structure it is generally not possible to distinguish between a combined spin flip (CSF) and a pure spin flip (SF) by means of polarization-dependent selection rules, as shown schematically in Fig. 1. Also, the study of the temperature dependence of the resonance

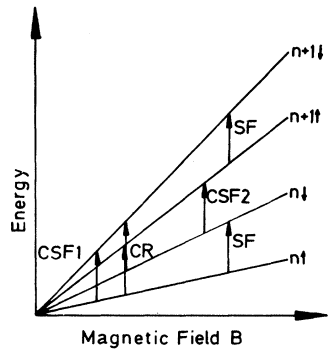

FIG. 1. The scheme for different magnetoresonances shows that pure spin-flip and combined spin-flip transitions may have about the same resonance position and then are difficult to distinguish.

lines will usually not succeed in proper identification since both cyclotron and spin-split energies exhibit the same temperature behavior in ordinary semiconductors.

We propose here a completely novel method for the unambiguous discrimination between those transitions, namely, "spin doping," and demonstrate its efficiency by application to the semiconductor HgSe. This new method affects in a well-controlled way the temperature dependence of the electron g factor, but has only negligible influence on the other characteristic quantities of the energy-band structure. Spin doping is easily achieved by substitution of only a very small amount of crystal ions by paramagentic ions, such as, for example, Mn, Fe, or Co. It is well known that for such a semimagnetic semiconductor $A_{1-x}M_xB$ the effective g factor is of the form[1]

$$g = g_0 + Jx\langle S_z\rangle/\mu_B H. \quad (1)$$

Here g_0 is the g factor of the undoped material, μ_B is the Bohr magneton, and H is the magnetic field.

For a mole fraction x of paramagnetic ions in the crystal of the order of 10^{-3} times the energy gaps, this means essentially that the other band-structure parameters are to a very good approximation those of the undoped material AB. In Eq. (1) J is the s-d exchange coupling constant, and $\langle S_z\rangle$ is the thermal average of the localized spin of the dopant along the magnetic field axis. The quantity $\langle S_z\rangle$ is usually a very sensitive function of the temperature and therefore the temperature control provides a direct means of controlling the spin splitting. It should be noted that for very high temperatures the average polarization $\langle S_z\rangle$ vanishes, so that in this limit the band structure merges into that of the undoped material.

Because of the temperature dependence of the effective g factor the three different resonance transitions exhibit characteristic temperature behavior: The cyclotron resonance should, in this approximation, not be affected by temperature, whereas the CSF2 transition should exhibit the opposite sign in the temperature shift in comparison with the CSF1 and SF transitions.

After the magnetotransmission measurements on HgSe by Pastor, Jaczynski, and Furdyna[2] the question concerning the correct assignment of spin-flip and combined spin-flip transitions to the resonance lines observed so far entered into discussion, and a new $\vec{k}\cdot\vec{p}$ parameter set differing from the established one[3] has been proposed. To check the interpretation of our former results on HgSe,[4] we applied the spin-doping method and investigated $Hg_{1-x}Mn_xSe$ for $x = 0.0015$, that means for only a very small Mn composition in the mixed-crystal system. The experimental method was submillimeter magnetospectroscopy using the strip-line technique.[5] The carefully annealed and etched sample was investigated in the parallel configuration which is dominated by the ordinary Voigt mode. It was oriented with the [001] direction parallel to the magnetic field. Applying several wavelengths varying from 70.6 to 570 μm of an optically pumped laser system in magnetic fields up to 20 T, we were not only able to follow the frequency dependence of the observed resonance lines, but also to record in the long-wavelength limit the optical Shubnikov–de Haas effect,[5] which provides the necessary information for the carrier concentration and hence the Fermi energy in the sample. The *experimentum crucis*, however, was the investigation of the temperature dependence of the observed resonance lines, as demonstrated for 170.6-μm-wavelength radiation in Fig. 2. The shift of the β line towards lower magnetic field intensities for increasing temperature, that is, for decreasing g factor, proves definitely that the resonance is caused by a CSF2 ($N\uparrow \rightarrow N+1\downarrow$) transition, whereas the α line, because of its opposite temperature dependence, is due to a CSF1 ($N\downarrow \rightarrow N+1\uparrow$) transition. These transitions are schematically indicated in the plot of Landau levels in Fig. 3. The levels were calculated for Mn-doped material ($x = 0.0015$, solid curves) and pure HgSe ($x = 0$, broken curves) using the model of Dobrowolska *et al.*[6] for a temperature of 4.2 K. The solid arrows represent the highest possible observed transitions near the Fermi energy (dashed hori-

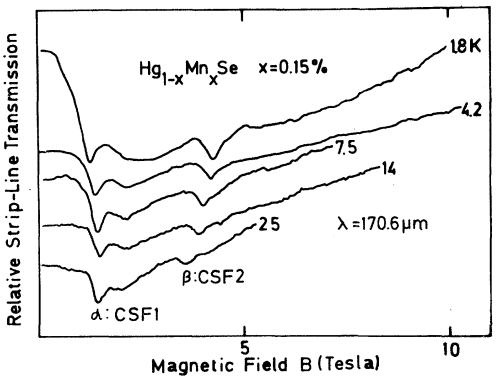

FIG. 2. The temperature dependence of the observed resonances in $Hg_{1-x}Mn_xSe$, $x = 0.0015$, proves clearly that the α and β lines are caused by the CSF1 and CSF2 transitions, respectively.

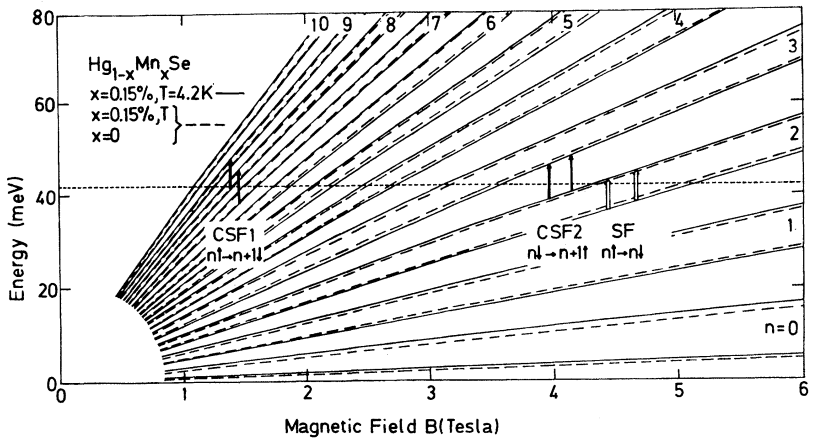

FIG. 3. The scheme of Landau levels for $Hg_{1-x}Mn_xSe$ ($x = 0.0015$, $T = 4.2$ K) as plotted by the solid curves has only a slightly larger spin splitting than that for pure HgSe represented by the broken curves. The full arrows indicate the observed transitions of 170.6- and 163-μm-wavelength radiation near the Fermi energy of $\delta = 43$ meV; the pure spin flip, as indicated by the open arrows, was not observed in our experimental results.

zontal line) for 170.6- and 163-μm-wavelength radiation, respectively. The open arrows indicate the magnetic field position of the corresponding pure spin-flip transition, which is, astonishingly, not observed in our experiment. It should be noted that both SF and CSF2 transitions are not allowed in a simple isotropic model, but require an additional perturbation mechanism which breaks the angular-momentum selection rule.

We hope that this demonstration of the efficiency of the spin-doping tool in the investigation of the band structure of HgSe will stimulate its further application with other materials.

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