Threshold singularity in the distribution of the conduction electrons of *n*-InSb under resonant scattering by ionized impurities in a quantizing magnetic field

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We have detected concentrational anomalies of the position and amplitude of the spin resonance in the nonlinear optical susceptibility of the conduction electrons in InSb. These effects can be explained by a restructuring of the dispersion relation of the electrons in a quantizing magnetic field as a result of resonant scattering by impurities.

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Owing to the presence of singularities in the electronic density of states at the bottom of each of the Landau sub-bands in a quantizing magnetic field, the scattering of carriers can become strong and cause renormalization of the dispersion relation. Of particular interest is the case when the scattering process is characterized by a certain energy threshold. Near the threshold the restructuring of the distribution is very substantial (see, for example, the review by Levinson and Rashba,[1] where the magnetopolaron problem is discussed in detail).

In this letter we report the experimental detection of the restructuring of the distribution of conduction electrons in the narrow-band semiconductor InSb due to the scattering of electrons by ionized impurities in a quantizing magnetic field. In this case the threshold energy is the energy of the bottom of the higher (unfilled) Landau band, and the process which leads to the restructuring of the distribution is the scattering between Landau sub-bands with different quantum numbers N.

The restructuring of the electron energy distribution was detected by investigating the nonlinear process of optical frequency combination in a magnetic field (the frequency combination was of the form $\omega_3 = 2\omega_1 - \omega_2$, where ω_1 and ω_2 are the CO_2-laser pump frequencies and ω_3 is the combination frequency). The nonlinear optical susceptibility responsible for this process $\chi^{(3)}(-\omega_3,\omega_1,\omega_1,-\omega_2)$, has a resonance when the difference of the pump frequencies $\Delta\omega = \omega_1 - \omega_2 \simeq 100\ \text{cm}^{-1}$ coincides with the spin frequency ω_s of the conduction electrons; we shall refer to this as a spin resonance. Thus, although it is the radiation power at the combination frequency P_{ω_3} that is measured in the experiment as a function of the static magnetic field, the resonance that is detected occurs not at the frequency of observation, but at frequency $\Delta\omega$. The measurements were made on InSb samples with electron concentrations of from 3×10^{16} to $1\times10^{17}\ \text{cm}^{-3}$ at liquid-helium temperature ($\sim$2 K). The experimental details are described in Ref. 2.

Figure 1 shows examples of the recorded spin-resonance signals for several samples of InSb with concentrations in the region where the anomalies of the spin resonance are observed. It is seen that while the amplitude of the spin resonance changes noticeably with changes in the electron concentration, the spin-resonance line shape remains practically unchanged. The concentration dependence of the position and amplitude of the spin resonance (more precisely, their dependence on the Fermi energy of the electrons) is shown in Fig. 2. One sees a sharp kink in the position of the spin resonance as a function of the concentration and a discontinuity in the amplitude of

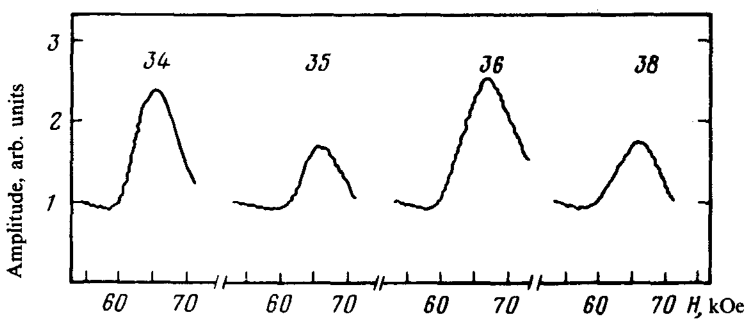

FIG. 1. Recorded signals of the spin resonance of the nonlinear optical susceptibility $\chi^{(3)}(-\omega_3,\omega_1,\omega_1,-\omega_2)$ of InSb as functions of the magnetic field for samples with different electron concentrations. The numbers above the curves correspond to the Fermi energies ϵ_F in meV for the given samples; the electron concentrations were $n = 6.8\times10^{16}\ \text{cm}^{-3}$ (34), $n = 7.1\times10^{16}\ \text{cm}^{-3}$ (35), $n = 7.3\times10^{16}\ \text{cm}^{-3}$ (36), $n = 7.9\times10^{16}\ \text{cm}^{-3}$ (38).

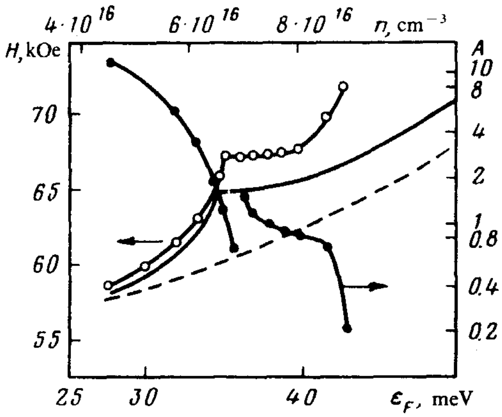

FIG. 2. Position and amplitude of the spin resonance of the nonlinear optical susceptibility as functions of the Fermi energy (concentration) of conduction electrons in InSb. The open points are the experimental positions of the resonance; the solid points are the experimental amplitudes of the resonance. The solid and dashed lines give the calculated positions of the resonance.

the spin resonance at the same value of the Fermi energy, $\epsilon_F \simeq 35$ meV.

To interpret these results, we examine the energy distribution of the conduction electrons of InSb in a quantizing magnetic field at values of the concentration and magnetic field in the region of interest.

Figure 3 shows the two lower Landau sub-bands (with quantum number $N = 0$) for the conduction electrons of InSb, which have different spin directions ($0\uparrow$ and $0\downarrow$), and a higher Landau band with quantum number $N = 1$ and spin $\uparrow (1\uparrow)$. In the concentration region of interest both the $0\uparrow$ band and the $0\downarrow$ band are occupied, but only wave numbers in the region where the $0\downarrow$ states are vacant and the $0\uparrow$ states are occupied (from k_1 to k_2 in Fig. 3) contribute to the resonance. The nonparabolicity of the dispersion curve causes the g factor to decrease for higher energies, so the position of the spin-resonance line should be monotonically shifted to higher magnetic fields as

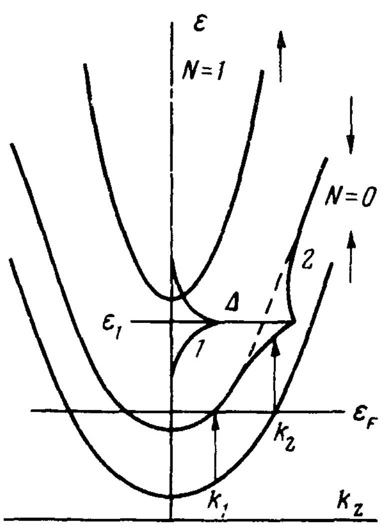

FIG. 3. Energy-level scheme. for conduction band of InSb in a magnetic field. Curve 1 describes the real part Δ of the intrinsic energy (level shift) for impurity scattering of $1\uparrow$-band electrons, curve 2 shows the renormalized disperion relation $\epsilon(k_z)$ of the $0\downarrow$ band near the threshold of interband scattering.

the concentration increases, while the amplitude should fall off smoothly owing to the decrease in the density of states. Such monotonic behavior of the position and amplitude of the spin resonance does in fact obtain at concentrations of up to 5×10^{16} cm^{-3}, the region which was examined in Ref. 2, but for the experimental results obtained in the present work the position of the spin resonance as calculated without allowance for the renormalization of the electron distribution due to scattering does not agree with experiment (dashed curve in Fig. 2).

The situation is altered substantially when the final states in the sub-band $0\downarrow$ for the electrons involved in the spin resonance fall within the region of wave numbers for which their energy is close to the energy of the bottom of the $1\uparrow$ band. When the energy of the final state reaches the energy ϵ_1 of the bottom of the $1\uparrow$ band, the electron can be elastically scattered by impurities from the $0\downarrow$ band to the $1\uparrow$ band: This scattering is resonant owing to the singularity in the density of states of electrons at the bottom of the $1\uparrow$ band. The energy ϵ_1 is thus the threshold of interband scattering. The total energy of an electron undergoing multiple scattering does not reduce to the energy of a free particle in a magnetic field, but contains a contribution from the energy of the electron in the field of the impurities (intrinsic energy). It is allowance for the intrinsic energy that leads to renormalization of the energy distribution both in the $1\uparrow$ band and in the $0\downarrow$ band; the intrinsic energy of an electron in the field of the impurities for these bands coincides with that of a spin flip to within a factor of the ratio of the probability of nonrelativistic intraband scattering to that of interband scattering.

Curve 1 of Fig. 3 depicts schematically the behavior of the real part of the intrinsic energy, which determines the energy shift and the restructuring of the distribution in the $1\uparrow$ band, as a function of the energy (reckoned from the threshold), and curve 2 shows the renormalized dispersion relation $\epsilon(k_z)$ for the $0\downarrow$ band. The calculations were done using a theory constructed in the spirit of the paper by Kubo *et al.*[3] The dependence of the position of the spin resonance calculated with the renormalized distribution is shown by the solid line in Fig. 2. To make the theory agree with experiment it was necessary to increase the electron-impurity interaction constants by a factor of two for scattering without a spin flip and by a factor of 15 for scattering with a spin flip. This is possibly due to the fact that scattering processes corresponding to Feynman diagrams with crossing lines were not taken into account in the theory.

Whether it is possible to observe the threshold singularity in the electron distribution depends very strongly on how the nonparabolicity of the dispersion relation affects the shape and width of the spin-resonance line. Because of this nonparabolicity, the precession frequencies of the resonant electrons will be smeared out over the interval $\Delta\omega_s=\omega_s(k_1)-\omega_s(k_2)$, so the spin-resonance line should be inhomogeneously broadened with a width $\Delta\omega_s$ (for $\tau_s^{-1}\ll\Delta\omega_s$, where τ_s is the spin relaxation time; this relation holds under the experimental conditions). In this situation, out of all the resonant electrons only a small group whose final states at the spin resonance fall in the neighborhood of the threshold will feel the effect of the threshold singularity. It might have been expected that the resonance line will have an inhomogeneously broadened profile with a slight feature due to this small group of electrons. In this case the presence of the threshold singularity would be detectable only by a method which separates out the contribution of this small group of particles (for example, by differentiation of the spin-resonance line).

However, the experimentally observed line shape does not change noticeably in the concentration region in which the anomalies of the position and amplitude of the spin resonance are observed (Fig. 1), and the presence of the threshold was reliably detected according to the concentration dependence of these characteristics of the spin resonance. The experimental results can be explained by taking into account the dynamical narrowing of the spin-resonance line.[4,2] Under conditions of intense momentum scattering the precession frequency of the electrons involved in the spin resonance is effectively averaged ($\tau_p \ll \tau_s$, where τ_p is the momentum relaxation time), and the shape of the resonance line is not inhomogeneously broadened, but is a Lorentzian of width $\delta\omega_s \sim \tau_p [\langle \Delta\omega_s^2 \rangle - \langle \Delta\omega_s \rangle^2]$. Thus, momentum scattering combines the resonant electrons into a single large group whose precession frequency is only slightly spread; these electrons fall within the region of the threshold singularity at practically the same value of the magnetic field. As a result, the nonparabolicity of the dispersion curve does not lead to either a strong smearing out of the effect of the threshold singularity or to a significant decrease in the fraction of the resonant electrons which feel the effect of the singularity.

The mechanism of resonant scattering of electrons by impurities may also explain the dependence of the spin-resonance amplitude on the electron concentration, since allowance for the intrinsic energy of the electrons in the field of the impurities leads to a density of final states near the threshold which has the same kind of singularity as is observed in the concentration dependence of the amplitude of the spin resonance.

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