# Spin-flip resonance in the photoconductivity and magnetoresistance of indium antimonide

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(Submitted 9 May 1982)
Pis'ma Zh. Eksp. Teor. Fiz. **36**, No. 4, 109–111 (20 August 1982)

In this paper, we report the first observation of the spin-flip resonance in photoconductivity and magnetoresistance, arising as a result of Raman scattering of light by free carriers in quantizing magnetic fields.

PACS numbers: 72.20.My, 72.40. + w, 78.20.Ls, 78.30.Gt

Transitions between the Landau spin sublevels in a semiconductor with Raman scattering of laser radiation of frequency $\omega_H$ is accompanied by generation of a new wave with frequencies $\omega_s$, satisfying the relation

$$\hbar\omega_s = \hbar\omega_H - g\mu H, \tag{1}$$

where $g$ is the effective Landé factor of conduction electrons ($n$-type semiconductors are being investigated), $\mu$ is the Bohr magneton, and $H$ is the magnetic field.

If a weak test signal with frequency $\omega_s$ is incident on a specimen simultaneously with the pump signal $\omega_H$, whose intensity is lower than the threshold for generating stimulated Raman scattering, then when condition (1) is satisfied, the latter will be resonantly amplified. Semiconductors, in contrast to insulators (liquids and gases), allows clarifying some fundamental details of such nonlinear interaction of laser radiation with matter, if in addition to the purely optical methods, electron-transport effects, which appear against the Raman-scattering background are used as well.

We investigated specimens of indium antimonide with degenerate ($n = 1.4\times10^{15}$ cm$^{-3}$; $u^{77} = 7.5\times10^5$ cm$^2$/B·s) and nondegenerate ($n = 10^{14}$ cm$^{-3}$; $u^{77} = 8\times10^5$ cm$^2$/V·s) electron gas. The experimental conditions and the optical scheme for measuring the gain $G(H)$ were analagous to that described in Ref. 1. The photoconductivity $\partial\sigma/\partial I$ was measured by the usual method of synchronous detection, while a battery of elements with high-ballast resistance was used as a current source. In order to measure the resonances in the magnetoresistance, for the purpose of excluding the monotonic component, we used the method of modulating the magnetic field and synchronous detection at the second harmonic,[2] which was successfully tested previously is studying magnetophonic oscillations in indium antimonide.[3]

The collinear radiation from two CO lasers was used as the pump and test signals and, in addition, the energy $\hbar\omega_H$ was chosen to be much greater than the width of the forbidden band of InSb, but such that interband absorption could be ignored compared to absorption by free carriers. The magnetic field was perpendicular to the direction of propagation of the radiation, along which a current was conducted and the potential difference was measured.

The photoconductivity curve (Fig. 1) for the degenerate specimen oscillates with

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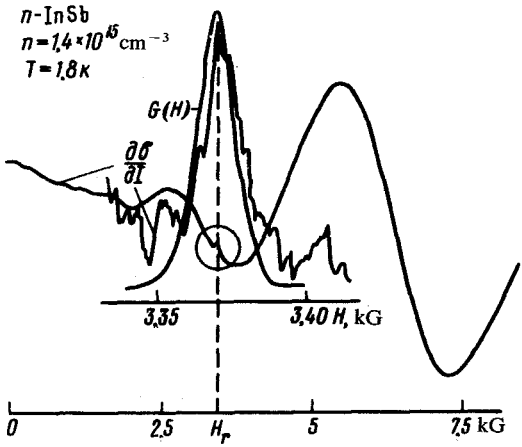


FIG. 1. Dependence of the photoconductivity on the magnetic field; $G(H)$ is the gain of the Stokes component.

increasing magnetic field and, in addition, the minima correspond to the position of the Shubnikov–de Hass maxima on the magnetoresistance curve. The spin-flip resonance (indicated by circles in Fig. 1) is manifested as a low peak with a magnetic field satisfying condition (1). At the center, this resonance $\partial\sigma/\partial I$ is shown in another scale, together with the gain $G(H)$, which represents the signal measured with a photodetector tuned to the Stokes frequency $\omega_s$. Thus, not only is the Stokes component of the scattered light amplified under condition (1), but a resonant growth in photoconductivity is also observed. This phenomenon could arise for two reasons: either a resonant change in concentration $n$ or conductivity $u$, since in general

$$\frac{\partial\sigma}{\partial I} = e\frac{\partial n}{\partial I}u + en\frac{\partial u}{\partial I}. \tag{2}$$

In order to clarify the contributions, we studied the behavior of the magnetoresistance near the resonance (1). It is well known[4] that in quantizing magnetic fields, the conductivity in a direction perpendicular to the magnetic field from 0 only in the presence of scattering. In addition, for nondegenerate statistics and scattering by impurity ions, the transverse magnetoresistance $\rho$ is nearly independent of the carrier concentration, but it is very sensitive to the change in the scattering process.

Figure 2 shows the dependence $\partial^2\rho/\partial H^2$ in the presence of radiation $\omega_H$ and $\omega_s$, together with the gain $G(H)$ and its second derivative. It is evident that magnetic-field modulation allows distinguishing the fine structure of the gain, which is completely repeated in the magnetoresistance. In degenerate specimens, we were able to observe the resonance in the magnetoresistance only in fields near the superquantum limit and higher, when in the absence of Raman scattering, electrons primarily occupy the lower spin sublevel.

The experimental data described above allow explaining the mechanism of the amplification of a weak signal with Raman spin-flip scattering.

It is customary to assume[5] that with nonlinear interaction of two waves in a medium at resonance (1), there is no change in the population of the levels, while the

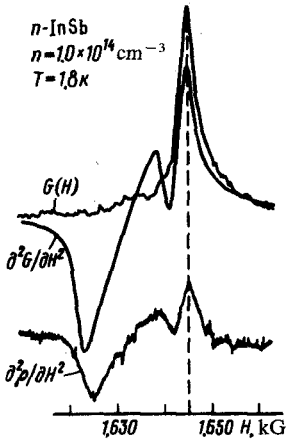


FIG. 2. The gain $G(H)$, its second derivative $\partial^2 G/\partial H^2$, and the second derivative of the magnetoresistance $\partial^2\rho/\partial H^2$.

increase in the test signal is explained only by the phasing of the spontaneous scattering and convergence of radiation in the direction of the test signal. However, the resonance in the magnetoresistance observed by us and the photoconductivity can arise only with excitation, at the time of resonance (1), of additional electrons into the upper spin level. Thus, the amplification of a weak signal with spin-flip scattering involves two processes: an increase in the degree of coherence of spontaneous Raman scattering, accompanied by focusing of the Stokes wave along the direction of the test signal, and an increase in the scattering intensity, leading to resonant increase in the population of the upper spin state.

In conclusion, we shall list the possible reasons for the change in mobility at resonance. First, due to the nonparabolic nature of the spectrum, the effective mass of the carriers in the lower and upper spin sublevels is different and, therefore, the mobility is different as well. Second, in the process of spin-flip relaxation, electrons make a transition to the lower level and are heated. The mobility of such carriers differs from the mobility of electrons located in the ground state.

The third reason is related to the localized spins, interaction with which leads to different mobility of electrons located in different spin levels. Finally, in degenerate specimens, in fields when electrons with $K_z = 0$ primarily participate in Raman scattering, carriers with energy of the order of the Fermi energy contribute to the conductivity at the lower level, while at the upper level, carriers with energy of the order of $K_0T$ contribute and the nature of their scattering by impurity ions is different.

The fact that we observed the resonance in the magnetoresistance only near the superquantum limit suggests that the last mechanism is primarily responsible for the change in the carrier mobility and formation of the resonance in the photoconductivity and magnetoresistance.

This work was carried out at Würtzburg University (German Federal Republic) and was financed by the Alexander von Humboldt Fund.

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Translated by M. E. Alferieff
Edited by S. J. Amoretty