Suppression of the paramagnetism of a semiconductor by a strong electric field

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It is shown that when the energy of the spin splitting in a magnetic field becomes a multiple of the energy of a step on the Wannier-Stark level in an electric field [G. H. Wannier, Phys. Rev. **117**, 432 (1960)], the spin contribution to the magnetic moment of the sample vanishes.

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We consider the energy spectrum of an electron in the conduction band of a semiconductor situated in parallel magnetic and electric fields directed along the z axis of the crystal. The magnetic field leads to Landau quantization in the xy plane, and the electric field leads to the appearance of Wannier-Stark levels. The electron energy spectrum takes in this case the form

$$\epsilon(l, n, \sigma_z) = Fal + \hbar\omega_c(n + \tfrac{1}{2}) + \mu\sigma_z H,$$

where F is the product of the electric field intensity and the electron charge, a is the lattice constant, l is the number of level of the Wannier-Stark ladder, ω_c is the cyclotron frequency, n is the number of the Landau level, μ is the effective magneton, σ_z is the quantum number (unity in a state with electron projection $\hbar/2$ on the z axis, and -1 when the projection is $-\hbar/2$), and H is the magnetic field intensity.

The magnetic moment of the sample at $H \neq 0$ is the sum of the spin and diamagnetic contributions. The purpose of this paper is to show the case that the fields are such that the energy $2\mu H$ of the spin splitting becomes a multiple of the energy Fa of the step of the Wannier-Stark ladder then the spin contribution to the magnetic moment of the sample vanishes and only the diamagnetic contribution remains. From the macroscopic point of view this means vanishing of the paramagnetic component of the sample's magnetic moment. The reason is the spin-orbit interaction, which causes the vanishing of the average value of the spin in the eigenstates of the Hamiltonian that takes the spin-orbit interaction into account.

Let us consider this case in greater detail. In fields $Fa \approx 2\mu H$ we have $\epsilon(l,n,1) \approx \epsilon(l+1,n,-1)$, and in this case we must take into account the spin-orbit interaction that mixes these states. In the new states the mean values of the spin is $\pm(\hbar/2)\lambda/\sqrt{\lambda^2 + 4|A|^2}$ (and not $\pm\hbar/2$ as in the case when no account is taken of the spin-orbit interaction), where $\lambda = Fa - 2\mu H$, A is the off-diagonal matrix element of the spin-orbit interaction. At $Fa = 2\mu H$ ($\lambda = 0$) the average spin is equal to zero and this leads to vanishing of the spin contribution to the magnetic moment of the sample. To observe the described effect it is desirable to produce in the semiconductor a quasi-stationary non-Boltzmann distribution of the electrons along the z axis, inasmuch as in the case of a Boltzmann distribution the electrons would be located mainly near the

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sample surface rather than at the Stark levels. The distribution over the remaining degrees of freedom will be assumed to be of the Boltzmann type with a temperature T. Assuming that the electron distribution along the z axis is uniform and that there are N electrons in the conduction bands, we obtain the following expression for the spin contribution to the magnetic moment of the sample

$$M_{\text{spin}} = N\mu \frac{\lambda}{\sqrt{\lambda^2 + 4|A|^2}} \text{th} \frac{Fa(1 - 2|b|^2) - \sqrt{\lambda^2 + 4|A|^2}}{2T}, \tag{1}$$

where

$$b = \frac{2A}{\sqrt{2\sqrt{\lambda^2 + 4|A|^2}}\ \sqrt{\sqrt{\lambda^2 + |A|^2} + \lambda}}$$

is a parameter that characterizes the degree of mixing of the states on account of the spin-orbit inetraction; when the mixing is large, $\lambda \approx 0$ and $|b| = 1/\sqrt{2}$, and $|b| \ll 1$ when the mixing is small.

In weak magnetic fields $2\mu H < Fa$ as well as in magnetic fields for which $Fa < 2\mu H < 2Fa$, the spin contribution (1) behaves in the usual manner and is equal to

$$M_{\text{spin}} = N\mu \,\text{th} \frac{\mu H}{T}. \tag{2}$$

At $Fa = 2\mu H$ ($\lambda = 0$) the spin contribution to the magnetic moment of the sample vanishes. The decrease of M_{spin} from (2) to zero and the return to (2) proceeds in a narrow interval of magnetic field intensities, on the order of $|A|/\mu$. The effect can be used to observe Wannier-Stark levels. On the other hand, if the sample is suspended in a magnetic field and an electric field $E = 2\mu H/ea$ is turned on, the sample will be acted upon by additional ponderomotive forces due to the turning off of the paramagnetic component of the magnetic moment.

Finally, we can attempt to observe the deviation of the maximum of the absorption of a semiconductor, as a function of H, in an EPR spectrometer in the indicated field region, and the appearance of two maxima in lieu of one.

[1]G.H. Wannier, Phys. Rev. **117**, 432 (1960).