Electron Spin Resonance on GaAs-$Al_xGa_{1-x}As$ Heterostructures

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Photoconductivity measurements on GaAs-$Al_xGa_{1-x}As$ heterostructures with photon energies 0.05 meV $<h\nu<$ 0.14 meV show resonance structures with a half-width of less than 0.002 meV in the magnetic field range 3 T $< B <$ 8 T. The resonances are only observed at magnetic field values where the Fermi level is located between spin-split levels and are attributed to electron spin resonance. The g factor depends on the carrier density. The linear extrapolation of the resonance energy to $B=0$ T leads to a finite excitation energy.

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It is well known that the electronic properties of a GaAs-$Al_xGa_{1-x}As$ heterostructure are mainly determined by the characteristics of an electron gas confined within a narrow potential well of some nanometers, usually called a two-dimensional electron gas (2D EG).[1] The carrier density of such a 2D EG is mainly determined by the donor concentration on the $Al_xGa_{1-x}As$ side, but can also be increased if the device is illuminated with infrared radiation at low temperatures.[2]

The discontinuity in the band structure at the GaAs-$Al_xGa_{1-x}As$ interface and the strong electric field in the potential well influences the interaction between different bands and should lead to a variation in the measurable band parameters like effective mass or electronic g factor.

This Letter reports electron-spin-resonance measurements on electrons in a heterostructure which demonstrate that the bulk parameters are affected by the interface potential.

The energy spectrum of the 2D EG becomes fully quantized if a strong magnetic field B is applied perpendicular to the plane of the 2D EG and can be approximated by the equation $E=E_0+(N+\frac{1}{2})\hbar\omega_c \pm sg\mu_B B$. The subband energy E_0 corresponds to the zero-point energy for the motion within the interface potential and the Landau quantum number $N=0,1,\ldots$ and the spin quantum number $s=\pm\frac{1}{2}$ characterize the energy for the motion in the plane of the two-dimensional system. The cyclotron energy $\hbar\omega_c=\hbar eB/m$ is usually known from both optical[3] (cyclotron-resonance) and transport[4] (Shubnikov–de Haas) experiments, whereas the spin splitting and therefore the g factor of a 2D EG in a heterostructure are determined exclusively from an analysis of magnetoquantum oscillations. Such measurements on GaAs-$Al_xGa_{1-x}As$[5] and GaInAs-AlInAs[6] heterostructures indicate that the g factor oscillates as a function of the occupation of spin-split levels with peak values $g^{\max}$ up to 5 times larger than the g factor known from measurements on bulk material. The g-factor enhancement is largest if the Fermi energy is located between spin-split levels and has been explained by the exchange effect among electrons in the Landau levels.[7]

Even without the enhancement of the g factor due to electron-electron interactions, the spin splitting in a two-dimensional system may be different from the bulk value. Calculations, which include the boundary conditions at the interface and interactions between different bands, demonstrate that the spin degeneracy, found in the one-band approximation for $B=0$, is lifted if the asymmetric interface potential and the spin-orbit interaction are included.[8,9] This means that even without magnetic field a finite spin splitting is expected. Bangert, von Klitzing, and Landwehr[10] obtained such a result in calculations of the two-dimensional *hole* spectrum of silicon inversion layers and similar data have also been published for the conduction-band states of a 2D EG in narrow-gap semiconductors like InSb (Ref. 9) and CdHgTe (Ref. 8) where the mixing between valence- and conduction-band states is relatively strong. Experimentally, the large g factor for InSb dominates the energy splitting in strong magnetic fields,[11] so that the additional splitting due to the removal of the inversion symmetry has not been resolved.

In principle, the absence of inversion symmetry in crystals with zinc-blende structure removes already the Kramers spin degeneracy of the bands for finite k values, but this splitting is negligibly small. This paper reports for the first time electron-spin-resonance measurements on a 2D EG which demonstrate that a finite spin splitting is present in the limit of zero magnetic field.

The samples had standard Hall geometry and consist of 1.5 μm of undoped GaAs on insulating GaAs, a spacer of 14 nm (sample 1) or 5 nm (sample 2) of undoped $Al_{0.3}Ga_{0.7}As$, 60 nm of Si-doped $Al_{0.3}Ga_{0.7}As$, and 20 nm of undoped GaAs. The resistivity ρ_{xx}, which is proportional to the voltage drop U_x between the potential probes under constant-current condition, is measured as a function of the magnetic field B. In addition, the ac component ΔU_x is recorded if the device is radiated with amplitude-modulated microwaves in the frequency range $\nu = 12$–35 GHz. The temperature in all experiments was typically 1.5 K. Electron-spin-resonance signals were only observed on devices with mobilities higher than 100 000 cm^2/V s at helium temperatures and the following data are obtained with different devices of two wafers with two-dimensional carrier densities of about 2.4×10^{11} cm^{-2} (sample 1) and 4.6×10^{11} cm^{-2} (sample 2), respectively. The experimental data are reproducible for different samples of the same wafer and Fig. 1 shows a typical result. In the magnetic field range up to $B = 7$ T, the spin splitting for the Landau levels $N = 1$ and $N = 2$ is visible at $T = 1.5$ K (inset in Fig. 1), and details of the experimental curves are plotted in the left part of Fig. 1 for Landau level $N = 2$ and in the right part for $N = 1$.

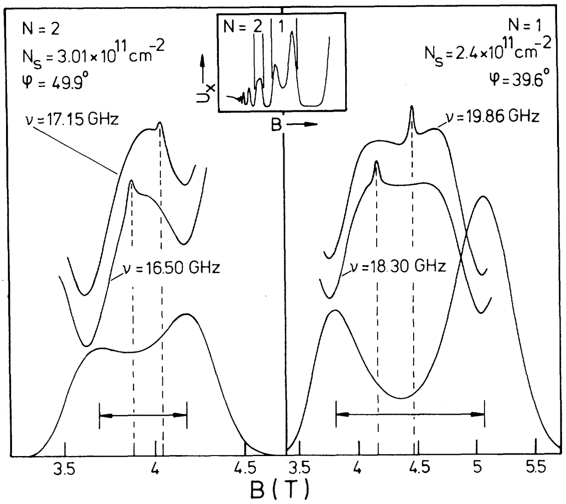

FIG. 1. Experimental data for the resistivity $\rho_{xx} \sim U_x$ and the photoresponse ΔU_x at different microwave frequencies ν as a function of the magnetic field. The spin-split levels for the Landau levels $N = 1$ and $N = 2$ are shifted to higher magnetic field by increasing the tilt angle φ between the magnetic field direction and the surface normal. Outside the magnetic field region characterized by the arrows the resonance signal in ΔU is reduced by more than a factor of 10.

Most of the photosignal ΔU_x arises from a frequency-insensitive heating of the electron gas which leads mainly to a signal proportional to the temperature modulation of the resistivity, $d\rho_{xx}/dT$. In addition a sharp resonance signal is visible with a resonance field position B which increases with increasing microwave frequency. This resonance structure is only visible in the magnetic field region where the Fermi level is located in the energy gap between spin-split Landau levels as expected for electron spin resonance (ESR). The amplitude of the resonance signal normalized to the bolometric background signal is reduced by more than one order of magnitude outside the magnetic field ranges characterized by the arrows in Fig. 1. It should be noted the magnetic field region where the ESR is measurable can be shifted to higher magnetic fields by increasing the carrier density (infrared illumination) or increasing the tilt angle φ between the surface normal and the magnetic field direction. A summary of the experimental data is shown in

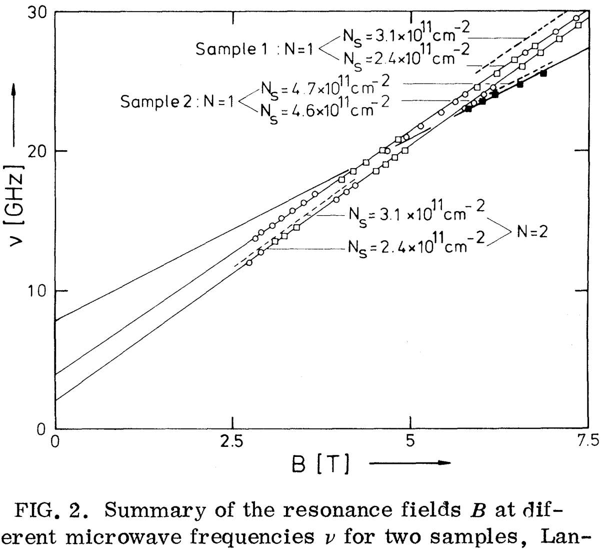

FIG. 2. Summary of the resonance fields B at different microwave frequencies ν for two samples, Landau quantum numbers $N = 1$ and $N = 2$, and different surface carrier densities due to different cooling processes (dotted lines).

Fig. 2. The magnetic field positions of the resonance are plotted as a function of the microwave frequency. In order to follow the resonance structure over a wide range of magnetic field, different tilt angles φ ($\varphi = 0°$, 40°, 50°, 57°, and 62° for Landau level $N = 1$ and $\varphi = 43°$, 51°, 61°, 64°, 72°, and 74° for $N = 2$) have been used for the measurements on sample 1, whereas the data for sample 2 are obtained at $\varphi = 0$. The dotted lines correspond to measurements on the same devices but higher surface carrier density N_s obtained after another cooling process from room temperature to helium temperature. A linear extrapolation to $B = 0$ leads always to a finite excitation energy. The results can be summarized in the following way.

The observed resonances attributed to ESR obey a law $\nu = \nu_0 + \alpha B$ (for 2.5 T $< B <$ 7.5 T) where the parameters ν_0 and α depend on the carrier density of the two-dimensional system, on the Landau quantum number, and slightly on the tilt angle φ. Drastic differences are observed for the two types of devices with different thicknesses of the spacer layer and therefore different two-dimensional carrier densities. The offset ν_0 increases approximately linearly with the surface carrier density and reaches the value 7.8 ± 1.5 GHz for the device with the carrier density 4.6×10^{11} cm^{-2}. Since the $\nu(B)$ curve must have a parabolic behavior close to $B = 0$, ν_0 represents a lower limit of the splitting. The slope α, which is proportional to the g factor, decreases with increasing carrier density. We found g factors of $|g| = 0.19 \pm 0.02$ for sample 2 and $|g| = 0.26 \pm 0.01$ for sample 1. These data are mean values for the spin splitting of Landau level $N = 1$ at different tilt angles. With increasing Landau level index, the energy separation of the spin levels (measured at the same total magnetic field but different tilt angles) decreases. An increase of the surface carrier density due to infrared illumination leads always to a shift of the ESR signal to higher energies, as shown in Fig. 3. In this figure, the variation of the resonance frequency at fixed magnetic field values is plotted as a function of the change in the carrier density due to infrared illumination. Within the experimental uncertainty $\Delta\nu$ increases linearly with the variation ΔN in the surface carrier density. The observed broadening of the resonance structure with increasing ΔN results from inhomogeneities in ΔN.

Most of the experimental data can be understood (at least qualitatively) as an interband effect caused by the interface field. Corresponding theories have been developed only for $Hg_{1-x}Cd_xTe$ (Ref. 8) and InSb (Ref. 9) but are basically valid for almost all semiconductors with zincblende structure. Since the interface potential has no inversion symmetry, the spin degeneracy of the conduction band is lifted by the spin-orbit interaction with an estimated splitting proportional to the Fermi wave vector and the effective electric field in the interface channel. Numerical calculations for InSb with a carrier density of 10^{12} cm^{-2} give a spin splitting of about 8 meV.[9] Similar calculations for GaAs are not available, but it seems to be reasonable that the relatively large energy gap for GaAs leads to the observed splittings which are about two orders of magnitude smaller than calculated for InSb. The absolute value of the measured splitting in strong magnetic fields is smaller than found for free electrons in GaAs. The published data for bulk GaAs vary between $g = -0.50$[12] and $g = +0.52$[13]; the most reliable value seems to be $g = -0.44$.[14] Since the wave function of the electrons in a GaAs-$Al_xGa_{1-x}As$ heterostructure penetrates into the $Al_xGa_{1-x}As$ side, it is not clear how strongly this material with a g factor of $g = +0.4$ at $x = 0.3$ (Ref. 14) influences the experimental data.

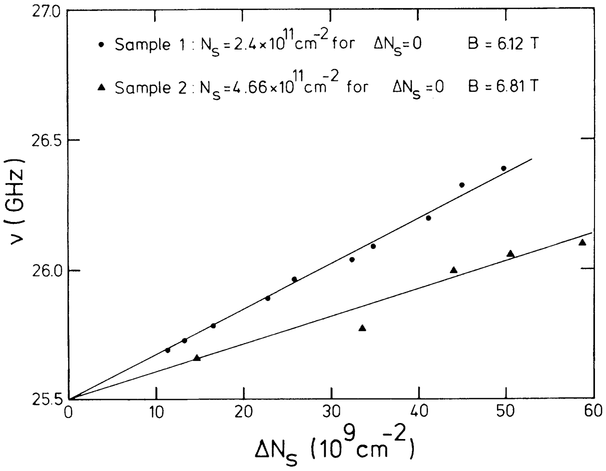

FIG. 3. Variation of the resonance frequency ν as a function of the change ΔN_s in the surface carrier density (determined from the Shubnikov–de Haas period after infrared illumination) for two different samples.

In conclusion, ESR measurements on electrons in GaAs-$Al_xGa_{1-x}As$ heterostructures show that in agreement with theoretical arguments there is a lifting of the spin degeneracy at $B = 0$ due to the interface field (removal of the inversion symmetry). The measured g factor at high magnetic fields is substantially smaller than the value determined from magnetotransport measurements. This result is not surprising because the many-particle correction to the g factor, which leads to an enhancement of the spin splitting in Shubnikov-de Haas experiments, cannot be observed in spin resonance. Our results indicate that electron-spin-resonance measurements seem to be a sensitive tool for studying interband effects caused by the interface field.

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