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PHOTOCONDUCTIVITY ON GaAs–$Al_xGa_{1-x}As$ HETEROSTRUCTURES

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The variation of the resistivity ρ_{xx} of GaAs–$Al_xGa_{1-x}As$ heterostructures at $T = 1.5$ K under far-infrared or microwave irradiation is analyzed as a function of the magnetic field. The observed resonances are attributed to cyclotron resonance and electric-dipole induced electron spin resonance.

Photoconductivity measurements on semiconductors, which are often more sensitive than absorption measurements, are mainly used for the detection of optical transitions between sharp energy levels. In this paper we present photoconductivity measurements on GaAs–$Al_xGa_{1-x}As$ heterostructures as a function of the magnetic field under microwave or far-infrared illumination.

The samples have standard Hall geometry and consist of 1.5 μm undoped GaAs on insulating GaAs, a spacer of undoped $Al_{0.3}Ga_{0.7}As$, 60 nm Si-doped $Al_{0.3}GA_{0.7}As$, and 20 nm undoped GaAs. The two-dimensional carrier densities are about 2.3×10^{11} and $4.6 \times 10^{11} cm^{-2}$ for spacers of 14 and 5 nm, respectively. The variation of the resistivity ρ_{xx} due to infrared radiation ($\lambda = 118$ μm and $\lambda = 337$ μm) or microwaves in the frequency range 12–35 GHz is measured as a function of the magnetic field. Photovoltaic signals are eliminated by analyzing the variation of the photosignal under AC conditions with an additional lock-in amplifier. The temperature in all photoconductivity experiments was typically 1.5 K.

A survey of experimental data is shown in fig. 1a. The upper two curves are Shubnikov–De Haas measurements for different temperatures. At $T = 25$ mK the spin splittings of the Landau levels $n = 1$ and $n = 2$ are clearly resolved, whereas the structure visible at a filling factor $\nu = 4/3$ at $T = 1.4$ K disappears below 300 mK. Since photoconductivity data are usually influenced by a

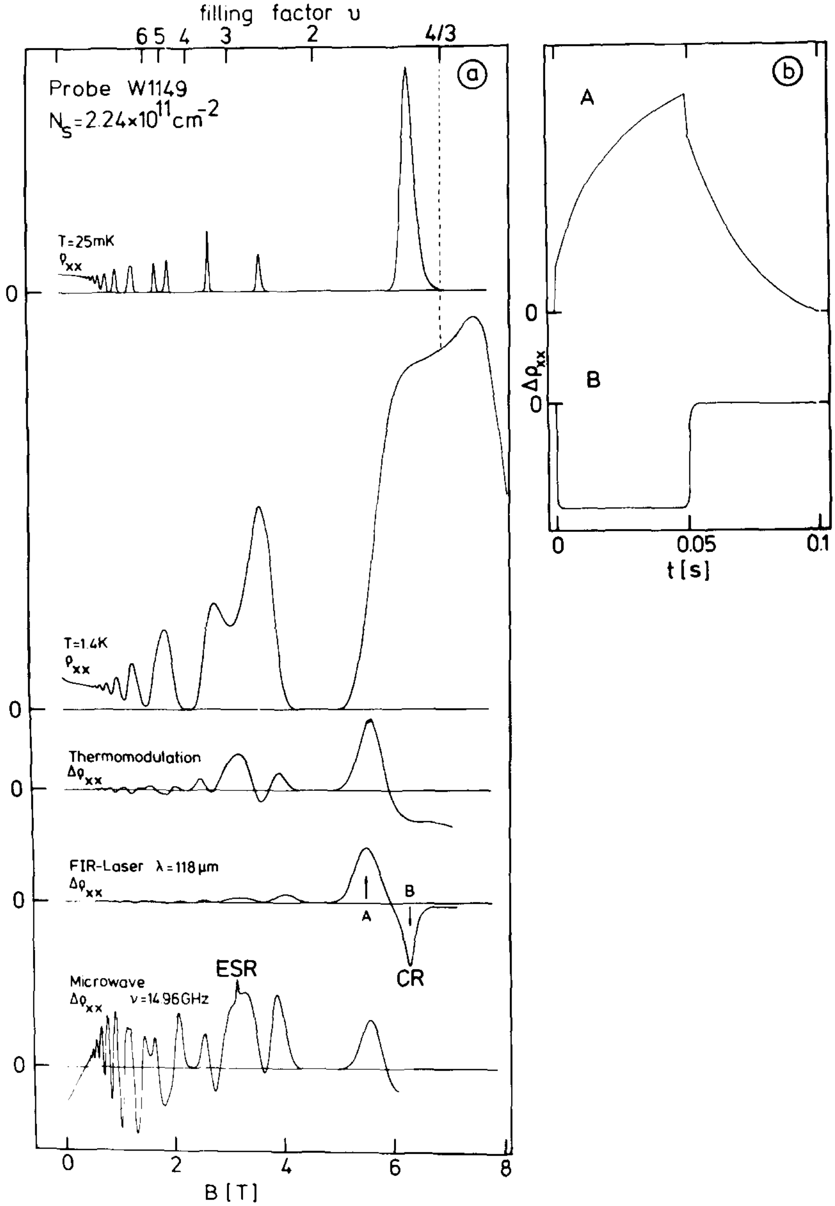

Fig. 1. (a) Resistivity ρ_{xx} and the variation of the resistivity ρ_{xx} under microwave or FIR radiation as a function of the magnetic field B. For comparison, the thermomodulation signal $\Delta\rho_{xx}/\Delta T$ is shown as well. The observed resonance structures are attributed to cyclotron resonance (CR) and electron spin resonance (ESR). (b) The time-dependence of the photosignal under FIR radiation ($\lambda = 118$ μm) at two different magnetic field values A and B (see (a)).

bolometric signal, the thermomodulation signal $d\rho_{xx}/dT$ is shown in fig. 1a, too.

The measurements under FIR radiation show usually a strong enhancement of the photosignal at the magnetic field of cyclotron resonance [1,2]. However, if the resonance lies in the plateau region ($\rho_{xx} = 0$), the absorption process is not visible in photoconductivity. This means that the lifetime of photoexcited carriers is extremely small. The time-dependence of the photosignal (fig. 1b) demonstrates that at least two different processes with different time constants contribute to $\Delta\rho_{xx}$. The amplitude and the sign of the contributions vary independently with magnetic field. The signal with a time constant of more than 10 ms is attributed to a modulation of the lattice temperature, whereas the fast response originated from an electronic process which leads to a change in the electron distribution function and in the simplest case to a variation in the electron temperature. We have no explanation for the fact that at the magnetic field position B (cyclotron resonance field) only the fast photosignal is visible. This result may indicate that radiative recombination is very effective under this condition. The photosignals plotted in fig. 1a are obtained at a chopper frequency of $f = 900$ Hz and correspond to the fast photosignal.

With microwave radiation, a new sharp resonance appears around $B = 3$ T at $\nu = 14$ GHz, as shown in the lowest curve of fig. 1a. This signal is attributed to spin resonance of free electrons (ESR) in the two-dimensional system. In principle any absorption process within the device may influence the resistivity of the two-dimensional electron gas (2DEG), but the following results indicate that the observed resonances are really connected with electronic states of the 2DEG:
(a) The resonance can only be observed, if the Fermi energy is located between spin-split levels. The amplitude of the signal has a maximum at filling factors

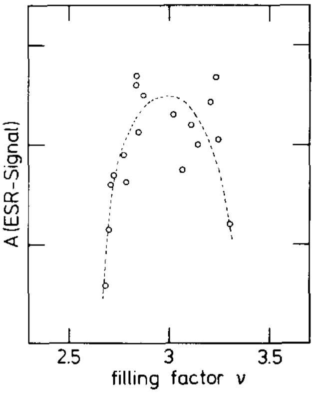

Fig. 2. Amplitude of the ESR signal (normalized relative to the background signal) as a function of the filling factor ν.

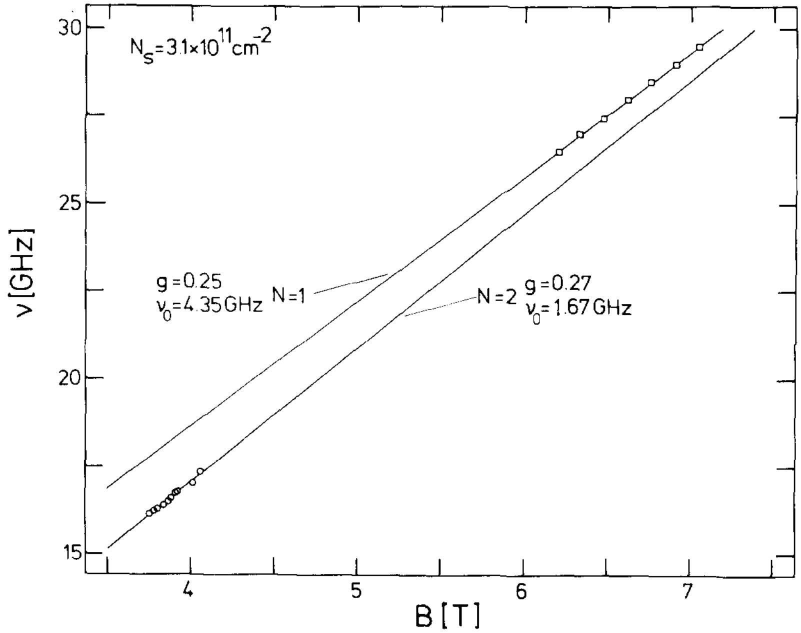

Fig. 3. Magnetic field positions of the ESR signal at different microwave frequencies ν for filling factors close to 3 ($N = 1$) and 5 ($N = 2$). The tilt angle of the magnetic field is $\phi \approx 50°$. The straight lines are characterized by the offset ν_0 and the slope $g\mu_B/h$.

close to $\nu = 3$ and $\nu = 5$. (The magnetic field for $\nu = 1$ is outside the experimental range and at $\nu = 7$, 9, 11, etc. the spin-splitting is not resolved.) A typical result is shown in fig. 2 where the normalized amplitude of the ESR signal is plotted as a function of the filling factor. The amplitude relative to $\nu = 3$ is reduced by more than one order of magnitude at $\nu < 2.5$ and $\nu > 3.5$.

(b) The resonance condition is a function of the Landau quantum-number N, as shown in fig. 3. For $N = 1$ (filling factor close to $\nu = 3$) the observed resonance obeys the law $\nu = 4.35$ GHz + $0.25\ \mu_B B/h$, whereas for $N = 2$ the relation $\nu = 1.67$ GHz + $0.27\ \mu_B B/h$ is obtained.

These experimental data demonstrate that the observed resonance under microwave radiation is connected with the electronic properties of the 2DEG and can be explained as electric-dipole induced electron spin resonance [3].

A summary of all experimental data related to the ESR signal is shown in fig. 4. 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 between the magnetic field and the surface normal have been used for the measurements on sample 1, whereas the data for sample 2 are obtained at $\phi = 0°$. The dotted lines

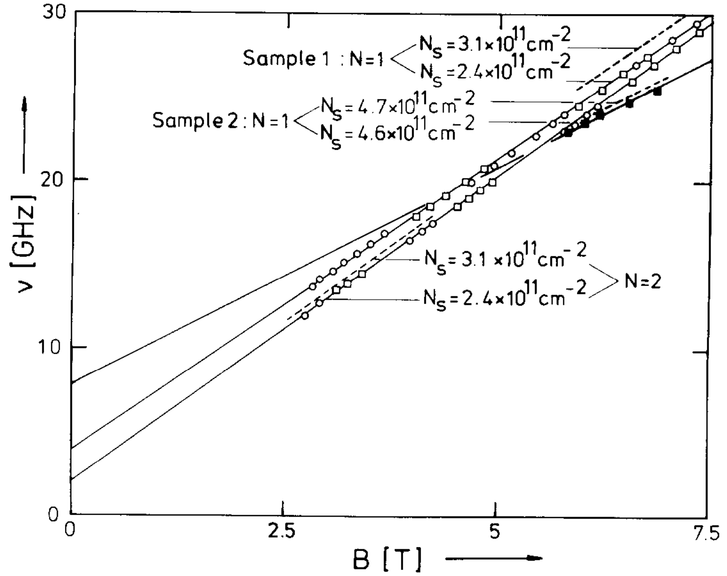

Fig. 4. Summary of the ESR fields B at different frequencies ν for two samples, Landau quantum numbers $N = 1$ and $N = 2$, and different surface carrier densities due to different cooling processes.

correspond to measurements on the same device but higher surface density N_s obtained after another cooling process from room temperature to helium temperature. A shift of the resonance energy to higher frequencies is also observed, if the carrier density of the 2DEG is increased by infrared radiation [4]. The extrapolation to zero magnetic field gives always a finite excitation energy.

All these experimental data are compatible with spin resonance of free electrons in the two-dimensional system. Especially the lifting of the spin-degeneracy at $B = 0$ T for a two-dimensional system without inversion symmetry has been predicted theoretically [5,6], but a quantitative theory is not available. A discussion of the experimental data on the basis of electron spin resonance will be published separately [4].

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