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MAGNETOTRANSPORT AND CYCLOTRON RESONANCE INVESTIGATIONS OF THE 2D ELECTRON GAS IN e$^-$-BEAM IRRADIATED AlGaAs/GaAs HETEROJUNCTIONS

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A 2D electron gas (2DEG) with a controlled density of repulsive scatters at the interface is obtained by irradiation of AlGaAs/GaAs heterojunctions with 1 MeV electrons. Measurements of the magnetotransport yield that the plateaus in the Hall resistance are at their quantized values $R_{xy} = h/e^2\nu$ (ν is the integer filling factor) but show a significant broadening. The lineposition $\hbar\omega_c$ of the cyclotron resonance is found to be shifted to higher energies such that $(\hbar\omega_c)^2 = (\hbar\omega_c^0)^2 + (\hbar\Omega)^2$ with $\hbar\omega_c^0$ the energy before irradiation and $\hbar\Omega \cong 30\ \mathrm{cm}^{-1}$. From the investigation on partially up to fully annealed samples we found that $(\hbar\Omega)^2$ is proportional to n_{sc}, the density of scatterers of the 2DEG.

Up to date, investigation of the cyclotron resonance (CR) in the AlGaAs/GaAs system mainly concerned nominally pure samples with preferably a high mobility of the two-dimensional electron gas (2DEG). The interest was focused on intrinsic effects like e.g. the polaron effects, subband coupling and the nonparabolicity of the bands. Extrinsic effects connected to interface states and defects are mainly investigated in Si MOS structures. In a number of papers anomalies in the effective mass and the linewidth of the CR were reported, e.g. ref. [1]. By common consent, those effects were ascribed to the interaction of the 2DEG with imperfections. However, the basis of this interaction could not be given in much detail [2]. The main problem was that the true nature of these defects was unknown and the defect density could not be controlled. We will present experiments on the magnetotransport properties of MBE-grown high mobility AlGaAs/GaAs heterostructures where defects were induced by electron irradiation (1 MeV) and removed by subsequent annealing of the sample.

Irradiation of the samples was carried out at LN_2-temperature with electron doses up to $2\times10^{17}\ \mathrm{cm}^{-2}$. The irradiation induced defects are mainly vacancy–interstitial pairs in the As sublattice [3]. These defects are connected to a number of electron traps in the bandgap of GaAs [3]. After irradiation the n^+-doped AlGaAs layer will be therefore partially compensated, and in addition a certain number of the 2D electrons will be trapped by defects located close to the

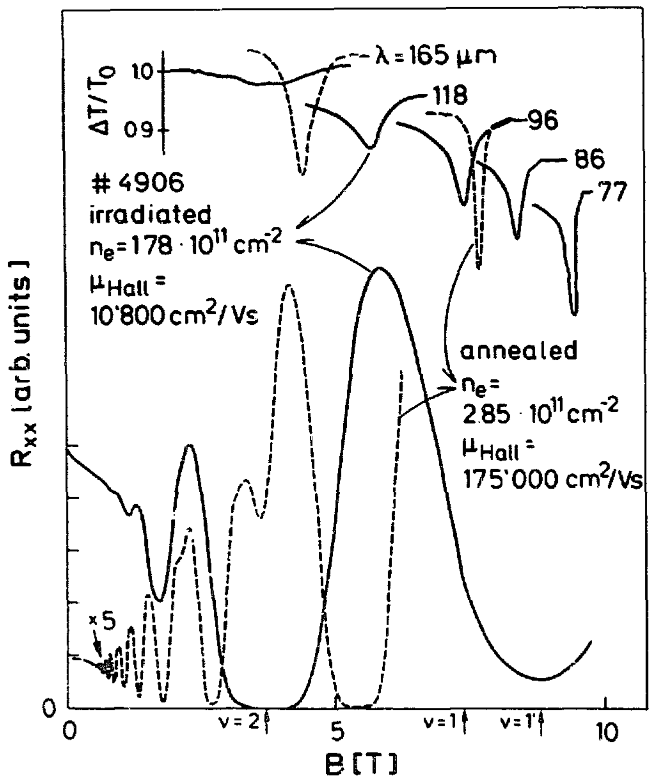

Fig. 1. Typical measurement of the longitudinal magneto resistance R_{xx} and of the CR transmission $\Delta T/T_0$ (at a temperature of $T \approx 1.5$ K) for an irradiated AlGaAs/GaAs heterostructure before (full lines) and after (dashed lines) a single annealing step.

AlGaAs/GaAs interface. Such an occupied electron trap acts as a repulsive scatterer for the 2DEG. DC transport and CR measurements are performed at $T \lesssim 2$ K. LED was used to increase the 2D electron concentration n_e. The CR is measured in transmission with the magnetic field and k-vector of incident radiation directed perpendicular to the sample interface plane. For the detailed measurements of the dependence on the magnetic field of lineposition, linewidth 2Γ = (FWHM) and amplitude of the CR, a fast scanning Michelson interferometer is used. In case of small and broad CR signals, e.g. for strongly irradiated samples with low n_e, the CR data are obtained using a CO_2-laser-pumped molecular gas laser.

Fig. 1 gives a general view of the DC and AC properties of an e⁻-irradiated sample (full lines), and of the same sample after a single annealing step at $T = 250$°C (dashed lines). After the irradiation the low temperature Hall mobility μ_e is dropped from its originally high value down to 10 800 cm²/V·s. After one annealing at 250°C, the mobility increases to $\mu_e = 175\,000$ cm²/V·s, half of its initial value. For the irradiated sample, the Shubnikov–de Haas oscillations of the longitudinal magnetoresistance R_{xx} are weak at low field, and at $B = 3.7$ T a very pronounced minimum of R_{xx} is observed. This minimum with $R_{xx} \approx 0$ appears at a magnetic field where the filling (ν) of the spin Landau levels (LL) is $2 = hn_e/eB$ (n_e determined from

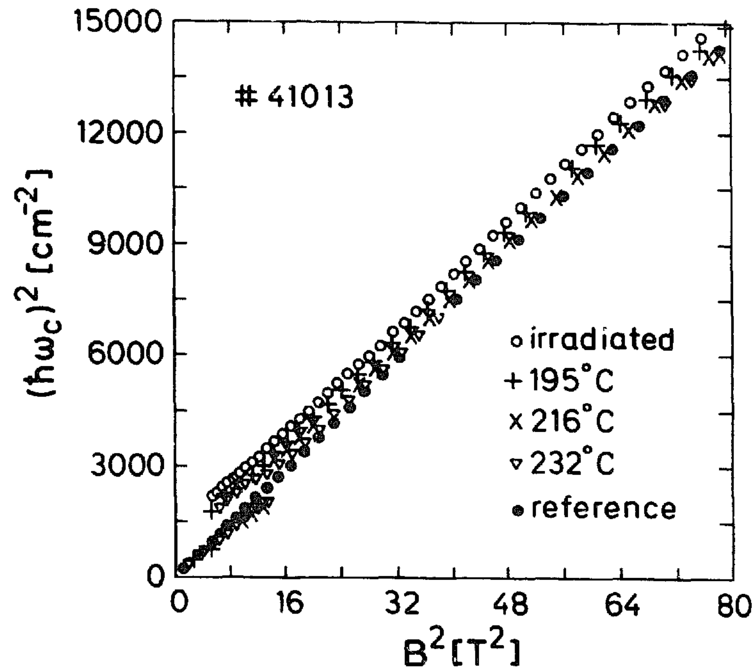

Fig. 2. Double quadratic plot of the CR lineposition $\hbar\omega_c$ versus the magnetic field B: for the irradiated sample (○), after annealing at $T=195°C$ (+), 216°C (×), 232°C (△) and finally for the reference sample (●).

low field Hall measurements). At this magnetic field a quantized Hall resistance $R_H = h/2e^2$ is observed. The expected relation between integer filling factor ν and minima in R_{xx} is not fulfilled for the minimum around $B = 8.8$ T since the minimum occurs at $\nu \approx 0.84$ but a quantized Hall resistance corresponding to $\nu = 1$ is observed. For the annealed sample, the minima in R_{xx} are narrower and steep and coincide with the expected position for integer filling factors. In the upper part of fig. 1 we see that irradiation apparently has a remarkable effect on both the linewidth 2Γ and the lineposition of the CR. At low magnetic fields, Γ is very broad: in fact $\mu_c\Gamma \approx 1$. For shorter wavelengths, i.e. higher magnetic fields, Γ gets successively smaller down to the value that was measured before irradiation. Annealing of the sample at 250°C (see fig. 1, upper part, dashed lines) leads to a reduced Γ and a shifted lineposition. We find that after complete annealing the linewidth as well as the lineposition of the CR is recovered that was measured before irradiation.

A better understanding of the shifted CR is obtained from a comparison of the lineposition of the CR measured after different stages of annealing. This is shown in a plot of $(\hbar\omega_c)^2$ versus B^2 in fig. 2. The shift relative to the reference sample (an unirradiated sample from the same wafer) becomes smaller and smaller with increasing annealing temperature. In this plot however, the shift appears to be independent of the magnetic field. We find that for $B^2 \gtrsim 16$ T^2, and for B small enough that nonparabolicity effects are not important, the squared CR energy is given by $(\hbar\omega_c)^2 \approx (\hbar\omega_c^0)^2 + (\hbar\Omega)^2$ where $\hbar\omega_c^0$ is the unshifted resonance energy and $\hbar\Omega$

some sort of pinning energy. For $B^2 \lesssim 16$ T^2 an additional CR transition appears which continues to zero field and behaves classically, i.e. broad linewidth with $\hbar\omega_c \approx \hbar\omega_c^0$.

Some of the features of the CR observed here remind of earlier CR measurements carried out on Si MOS structures at low densities with defects of unknown nature and concentration [1]. This however is different in our system: the irradiation induced defects are known to form electron traps. The trapped electrons are frozen out and therefore do not contribute to the 2D transport but they act as repulsive scatterers. Their number can be estimated from the dependence of the 2D-carrier concentration n_e on the annealing temperature. We found that n_e increases with increasing the annealing temperature up to $T \approx 300\,^\circ$C where the initial carrier concentration is recovered. However, the shift of the CR lineposition $\hbar\Omega$ and ΔB (the difference between the magnetic field position at the observed minimum of R_{xx} and its expected position for $\nu = 1$) are found to be very small after annealing at $T \approx 250\,^\circ$C already. For annealing temperatures $T \geqslant 250\,^\circ$C, anomalies in the CR lineposition and linewidth are still present, however they occur in a limited magnetic field regime close to $\nu = 2$ and look qualitatively very similar to what is found for unirradiated samples. We therefore believe, that the electron traps close to the interface are removed at first and that the annealing at $T > 250\,^\circ$C accounts for the recombination of the reamaining traps in the AlGaAs layer.

In fig. 3. a comparison is made for different annealing temperatures ($T \leqslant 252\,^\circ$C) of ΔB, n_e and the squared shift of the CR lineposition $(\hbar\Omega)^2$ deduced from fig. 2. The evaluation of $(\hbar\Omega)^2$ is limited by the determination of m_c at high field that was mentioned above. The straight lines in fig. 3 are drawn to show that the dependence on annealing is very similar for the three experimentally found quantities. For this, we have neglected the value for the irradiated sample of $n_e = 1.32 \times 10^{11}$ cm^{-2}. From the difference measured between the 2D-electron concentration after annealing at 195 and 252 °C we obtain a first value for the density of traps $\Delta n_e = 9.6 \times 10^{10}$ cm^{-2}. This value is an upper estimate for the density of repulsive scatterer n_{sc}, i.e. the traps close to the interface. A second estimate for n_{sc} we obtain from ΔB applying the analysis which is presented in a recent paper by Gerhardts, Haug and Ploog [4]. These authors investigated both experimentally and theoretically the DC-magneto transport properties of a 2DEG with a δ-layer of positively or negatively charged scatterers close to the interface. From their analysis it is known that the midpoint of the quantized Hall plateaus and the minimum of R_{xx} may differ from the expected position of integer filling factors if an asymmetric density of state is present. The asymmetry for a 2DEG where repulsive scatterers are dominant is such that ΔB is positive. Following their analysis and using the assumption given below, one obtains $n_{sc} \approx 2e\Delta B/h$ where ΔB is the difference between the magnetic field position of observed midpoint of the quantized plateau $R_{xy} = h/e^2$ respectively the minimum of R_{xx} and the expected position for filling factor $\nu = 1$. This expression is obtained if the δ-like scattering potential is strong enough to produce a gap between the impurity band of scattered states and the remaining

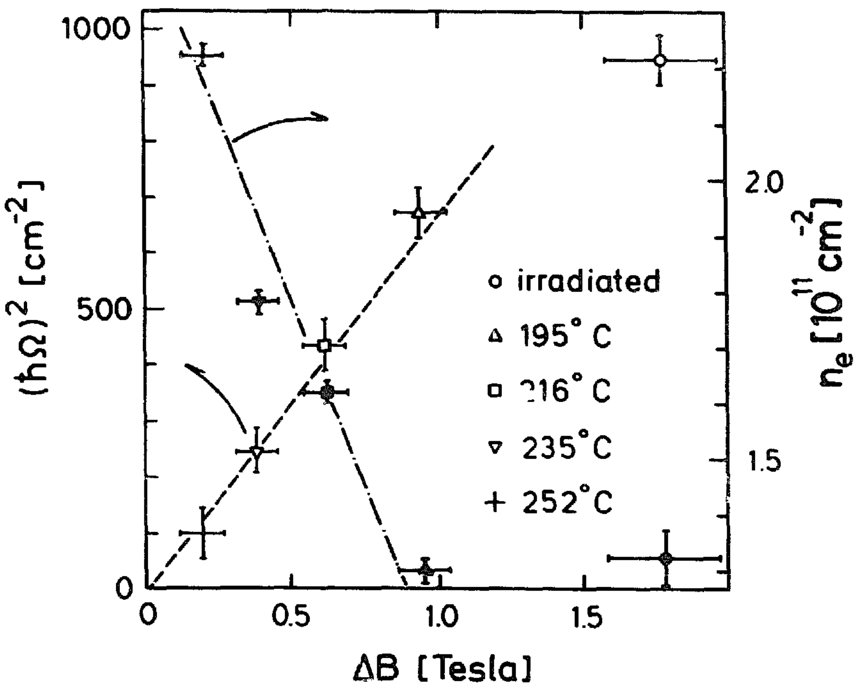

Fig. 3. Shift $(\hbar\Omega)^2$ of the square of the CR lineposition $(\hbar\omega_c)^2=(\hbar\omega_c^0)^2+(\hbar\Omega)^2$ (y-axis to the left, open symbols) and 2D-electron concentration n_e (y-axis to the right) versus ΔB, the difference between the magnetic field position of minimum of R_{xx} and its expected position for integer filling factor $\nu=1$.

states of the LL's. From the expression for n_{sc} and from fig. 3 we find for the irradiated sample and for the sample annealed at 195°C, $n_{sc}=9.2\times10^{10}$ cm^{-2} and $n_{sc}=4.9\times10$ cm^{-2} respectively. This is in good agreement with the upper bound deduced from $\Delta n_e=9.6\times10^{10}$ cm^{-2} and the observed linear relationship between n_e and ΔB. Although we do not know a model predicting the shift of the CR lineposition in details, from the analysis above and fig. 3 it is likely that $(\hbar\Omega)^2$ is proportional to n_{sc}. We have also investigated the dependence of ΔB and $\hbar\Omega$ on the 2D-electron concentration n_e by analysing measurements where n_e has been increased with a LED. It is found that ΔB and $\hbar\Omega$ do not depend on n_e. This is consistent with the picture that n_{sc} determines both ΔB and $\hbar\Omega$. Additionally, as it is shown in fig. 1 the occupation number of the LL's is found to be important. This is not unexpected because e.g. $\nu=2$ means that within a CR orbit each scatterer is surrounded by two electrons and therefore the effective scattering potential is reduced.

To summarize, we have shown a detailed experimental analysis of the magneto transport properties and the CR of e⁻-beam irradiated AlGaAs/GaAs heterostructures. We could make evident the origin of the shifted CR to come from the interaction of the 2D-electrons with repulsive scatterers.

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