RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 39, NUMBER 9 15 MARCH 1989-II

Cyclotron resonance in donor and acceptor δ-doped $Al_xGa_{1-x}As/GaAs$ heterostructures

J. Richter, H. Sigg, K. v. Klitzing, and K. Ploog
Max-Planck-Institut für Festkörperforschung, Heisenbergstrasse 1, 7000 Stuttgart 80, Federal Republic of Germany

(Received 17 October 1988; revised manuscript received 14 December 1988)

Cyclotron resonance experiments have been performed to study the influence of donor and acceptor impurities on the two-dimensional electron gas in $Al_xGa_{1-x}As/GaAs$ heterostructures. Two series of samples have been prepared doped with additional Si and Be at well-defined spacings from the interface and at various concentrations. A characteristic behavior of the cyclotron resonance specific to the doping species is found. Donor-doped samples exhibit a pronounced filling-factor-correlated oscillation of the linewidth and of the cyclotron effective mass. Acceptor-doped samples exhibit a second, frequency-shifted resonance over a wide range of magnetic fields, whose linewidth becomes extremely narrow at high magnetic fields and tends to an approximately constant value.

Impurities can strongly influence the cyclotron resonance (CR) of a the two-dimensional electron gas (2D EG). The enhanced scattering yields changes of the CR linewidth indicating the altered screening behavior in the 2D EG. Furthermore, anomalies in the CR lineposition are expected to occur due to impurity-mediated electron-electron interactions. Strong narrowing and a positional shift of the CR in Si metal-oxide-semiconductor (MOS) structures in the quantum limit[1] and a frequency-dependent cyclotron mass have been reported[2,3] and interpreted by the formation of a highly correlated or even crystallized ground state.[4] Similar observations have been made in molecular-beam-epitaxy (MBE) grown heterostructures, which are believed to have better interfaces due to almost perfectly lattice-matched growth. Filling-factor-dependent oscillations of the linewidth,[5,6] line splitting,[7] or strong linewidth narrowing in the quantum limit,[8] as well as oscillations of the cyclotron effective mass[9] have been observed. Although the explanations of the above-mentioned features in the CR of 2D EG mostly include some influence of impurities, no clear distinction between the influence of different species of impurities on the 2D EG has yet been made.

Motivated by systematic effects observed in e^--irradiated samples[10] and in the dc transport of impurity-doped 2D EG,[11] we started a comparative CR study on well-defined donor- and acceptor-doped $Al_xGa_{1-x}As/GaAs$ heterostructures. In the present work we report on specific differences in the CR of 2D EG under the influence of ionized donors as well as acceptors, i.e., attractive and repulsive scatterers, and present strong evidence for impurity-induced CR anomalies.

The investigated samples were $Al_xGa_{1-x}As/GaAs$ modulation-doped heterostructures, in which a δ layer of donor (Si) or acceptor (Be) dopant has been built in on the GaAs side during the MBE growth.[12] Except for the doping, all samples were grown under similar conditions, i.e., on semi-insulating GaAs substrates at temperatures of 530–550 °C with a background *p*-type doping level of about 1×10^{14} cm^{-3}. The dopant concentration was estimated by extrapolating values from heavily doped GaAs to low densities and ranged between 3×10^9 and 4×10^{10} cm^{-2}.

Due to the low growth temperature to avoid diffusion, the dopant is believed to be located within a few monolayers and thus at a well-defined distance Δz from the interface. The investigated range was $2.5 \leq \Delta z \leq 30$ nm. Sample mobilities ranged from 3×10^4 cm^{2}V^{-1}s^{-1} to 9×10^4 cm^{2}V^{-1}s^{-1}, depending on the built-in impurity concentration. The carrier densities were 1.8×10^{11} cm^{-2} $\leq n_s \leq 5.4\times10^{11}$ cm^{-2}, where the higher densities were achieved by *in situ* illumination. As a reference, a high-mobility heterostructure with a mobility of 5×10^5 cm^{-2}V^{-1}s^{-1} was studied. The samples were usually 4×6 mm^2 in size and, to avoid spurious interference effects, they were wedged at an angle of 2°. On the top, six Ohmic contacts in Hall geometry were used for the determination of the 2D electron density from Shubnikov–de Haas (SdH) oscillations. CR was performed in magnetic fields up to 14 T with a fast-scan Fourier-transform spectrometer or a CO_2-pumped far-infrared molecular gas laser. The incident radiation was guided from the source to the sample via an oversized waveguide and was focused on the sample with a Winston cone. The transmitted radiation was detected by a Ge bolometer placed well below the applied magnetic field. All measurements presented here were performed at 2.2 K.

Figure 1 shows the CR over the whole range of investigated magnetic fields for two samples of similar carrier mobilities, but with different types of doping. A strikingly different CR behavior is observed for the two differently doped heterostructures: The CR of the Si- (donor) doped sample shows a remarkable oscillatory behavior [Fig. 1(a)]. At minimum peak values we observed a strongly asymmetric line profile pointing to an additional resonance on the low-energy side. The Be- (acceptor) doped sample at low-magnetic fields also shows a broad resonance. However, towards high magnetic fields, a *second* resonance appears at higher energies, gains in oscillator strength, becomes extremely narrow, and finally remains the only observable resonance [Fig. 1(b)]. This resonance will be referred to as "high-field" CR.

The CR oscillation of the Si-doped sample is correlated

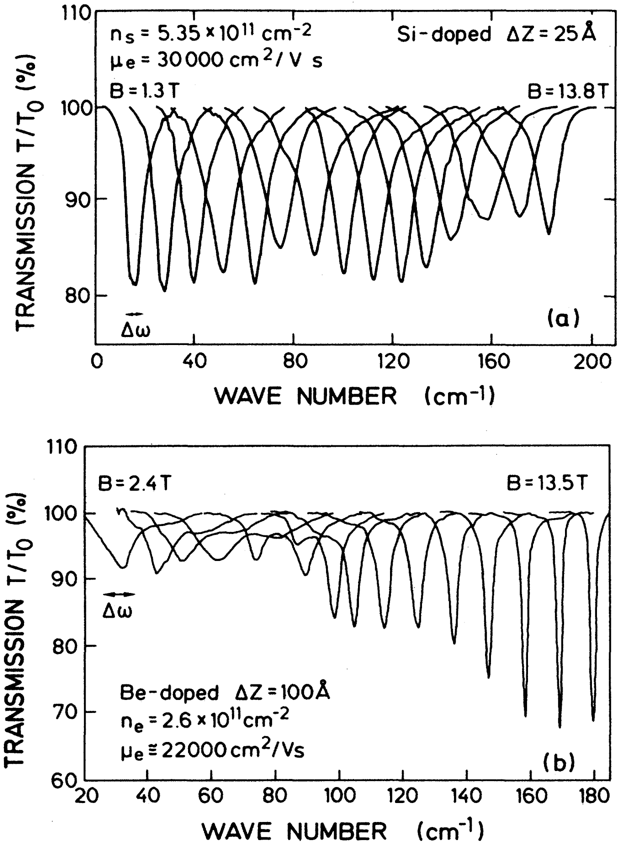

FIG. 1. Normalized CR transmission spectra, measured at $T=2.2$ K and at various magnetic fields of constant increment within the indicated ranges for (a) Si-δ-doped (with $n_{Si}=4\times10^{10}$ cm^{-2}) and (b) Be-δ-doped $Al_xGa_{1-x}As/GaAs$ heterostructures (with $n_{Be}=2\times10^{10}$ cm^{-2}). $\Delta\omega$ is the CR linewidth calculated from the dc mobility μ_e.

to the filling factor $\nu = n_s h/eB$ [Fig. 2(a)]. The linewidth $\Delta\omega$, taken from full width at half maximum, is narrow around *odd* and broad around *even* ν. The maxima of the linewidth, however, occur at slightly higher magnetic field values than the corresponding minima in the SdH oscillations, which were used to determine ν. The linewidth at $\nu=1$, 3, and 5 is essentially independent of the magnetic field but for lower fields, the linewidth gradually decreases with decreasing field.

The onset of the drastic reduction of the CR linewidth in the Be-doped case is also ν correlated. The CR linewidth starts to decrease around fields corresponding to $\nu=2$. Close to $\nu=1$ the linewidth approximately reaches its smallest value of 1.3 cm^{-1} and remains constant for higher fields. This behavior can be observed for all our acceptor-doped samples and is in contrast to donor-doped samples where, even in the high-field limit ($\nu\leq2$), such a drastic narrowing is never observed. At low magnetic fields $\nu\gg2$, in both Si-doped and Be-doped samples, the linewidth corresponds to the expected values based on the self-consistent Born approximation (SCBA) using the respective dc mobility of the samples:[13] $(\Delta\omega)^2=\omega_c^2(2/\pi)(\mu_e B)^{-1}$. ν-dependent linewidth oscillations are also observed in the low-field CR of some high-n_s Be-doped samples, but are most clearly seen in the high-n_s Si-doped samples.

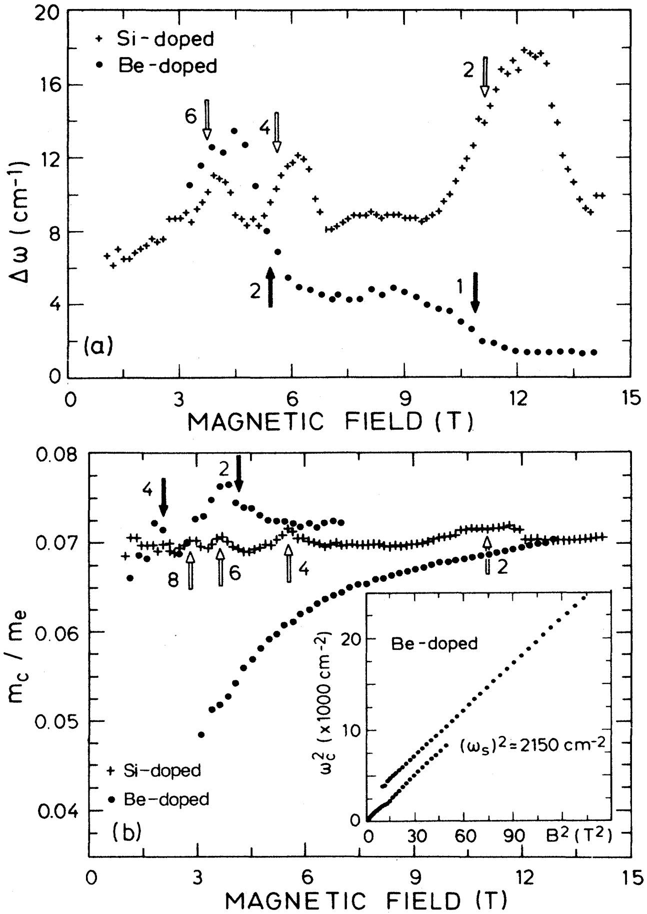

FIG. 2. (a) CR linewidth behavior for Si-δ-doped (+) and Be-δ-doped (●) heterostructures. For the Be sample only the linewidth data of the "high-field" resonance is plotted. The arrows indicate the filling factors (ν), obtained from Shubnikov–de Haas measurements. (b) Normalized cyclotron effective mass m_c/m_e for two different δ-doped heterostructures. Note the increased m_c at exactly even ν for the Si-doped sample and the strong reduction of the "high-field" m_c branch for the Be-doped sample. The inset depicts the quadratic plot $\omega^2=\omega_c^2+\omega_s^2$ vs B^2.

Specific differences between the two differently doped series can also be observed when the resonance position is studied. In Si-doped samples slight shifts in the position of the peak minima of the CR could be detected which, when expressed in terms of cyclotron mass $m_c=eB/\omega_c$, also lead to a ν-correlated m_c oscillation with maxima at exactly *even* ν [Fig. 2(b)]. These maxima are concomitant with the appearance of the low-energy resonance mentioned above, whose relative position to the CR depends on the magnetic field. Before even ν, where the CR linewidth is largest, the resonances are well apart but at even ν, both resonances merge into one broad, symmetric resonance. For Be-doped heterostructures, starting from low fields, the single resonance yields m_c values similar to the Si-doped case, and interestingly, also shows an oscillatory structure. However, close to $\nu=2$, the additional *second* absorption line exhibits a considerably reduced effective mass, which increases with increasing field towards the low-field value of $m_c \simeq 0.07 m_e$, The inset of Fig. 2(b) shows the dependence of the high-field-CR position in a plot of ω^2 vs B^2, which is well described by $\omega^2 \simeq \omega_c^2 + \omega_s^2$ with $\omega_c = eB/m_c$, and ω_s describing the additional shift.

All effects, i.e., the CR broadening and the amplitude of the linewidth oscillations and of the m_c oscillations in the Si-doped systems, as well as the amount of CR splitting ω_s in the Be-doped systems, vary monotonically as a function of dopant concentration. This suggests a collective influence of the impurities on the CR, in contrast to the well-known isolated impurity resonance behavior in the bulk. Note, however, that the linewidth of the high-field CR at $\nu \leq 1$ is only influenced by the ionized donors and is practically unaffected by the acceptor doping level. A detailed study regarding concentration dependences will be presented elsewhere.

Additional evidence for the specific influence of ionized impurities on the CR of 2D EG is obtained from the comparison of our data with previously published results. Englert *et al.*[5] observed oscillations of the CR linewidth in $Al_xGa_{1-x}As/GaAs$ heterostructures with thin spacers to the Si-doped $Al_xGa_{1-x}As$ We also observe the CR-linewidth oscillations most clearly in the Si-doped heterostructures. Furthermore, a closer look to the same data reveal that the observed maxima in linewidths do not occur at exactly even ν, but are shifted to smaller values, in agreement with our observations. A less clear correspondence is found with the data of Heitmann *et al.* on nominally undoped GaSb/InAs quantum wells. The much stronger linewidth oscillations occur exactly at even ν, but, owing to the band structure, they might be due to attractive scatterers as well.

The oscillatory behavior of the CR linewidth has been found to be described qualitatively by theoretical considerations[13–16] of the density of states (DOS) at the Fermi level E_F. As the magnetic field is varied, E_F passes through energy regions of changing DOS. This gives rise to an oscillatory screening behavior, oscillating scattering time and therefore oscillating CR linewidth. However, these models predict an unaltered CR position and linewidth maxima at exactly even ν, and therefore do not completely describe our observations.

Asymmetry in the CR line profile and changes in the cyclotron mass have been observed previously by Thiele *et al.*[9] and have been attributed to a transfer of oscillator strength between transitions involving different Landau levels (LL). Our data, though, shows clearly a dependence on the impurity concentrations, indicating that impurities affect observed cyclotron masses. The proposed influence of nonparabolicity cannot account for the strong effects observed in our samples. In fact, the appearance of the low-energy resonance rather suggests a possible coupling to other modes (e.g., magnetoplasmons[17]) which influence the CR position and CR linewidth. This coupling might be responsible for the observed disagreement with SCBA.

On the other hand, the occurrence of a *second*, narrow and shifted absorption line in acceptor-doped samples bears much resemblance to previous data presented by Wilson, Allen, and Tsui[1] in Si-MOS systems and by Schlesinger and co-workers in high-mobility $Al_xGa_{1-x}As/GaAs$ heterostructures.[7,8] The former study invoked the formation of an impurity-pinned, highly correlated electronic ground state. In the latter work, an impurity-mediated coupling of the CR mode to a softened magnetoplasmon mode was proposed to cause either broadening or splitting of the CR, and $\nu=1$ was found to be a distinct state of the system. Our experiments with acceptor-doped systems, however, suggest that around $\nu=2$ the system starts to undergo some transition, whose final state is reached around $\nu=1$, where the linewidth approximately reaches its smallest value, remaining roughly constant for higher fields, very much as described in Ref. 8.

Because such a transition to a narrow CR line has systematically been observed only in acceptor-doped systems, i.e., Be-doped and e^--beam-irradiated samples,[10,18] and has never been observed in donor-doped samples, an explanation must consider the different nature of the scattering processes. This difference does not emerge from the widely used SCBA calculations, since there the scattering form factor enters quadratically and thus does not make any distinction between differently charged scatterers. For the same reasons an impurity-induced coupling to magnetoplasmons[7,8] cannot account for the observed differences.

We explain the drastically different behavior of the CR for donor- and acceptor-dominated systems by the different distribution of the density of states in the two systems. In donor-doped samples the scatterers are positively ionized and it is most favorable for the electrons to be close to the scatterers. For the acceptor system the electrons avoid the repulsive Coulombic centers formed by the negatively ionized acceptors. As shown by Prange,[19] the scatterer-induced states for donor-doped samples correspond to states at the low-energy side of the LL states. They are thus occupied for all ν, leading to pronounced scattering. For the acceptor-doped samples the scatterer-induced states are higher in energy than the LL states. Therefore, we suggest that the narrowing of the CR in the quantum limit arises from the fact that the electrons populate only pure LL states in the lowest spin-split LL and no scatterer-induced states are occupied. This simple model explains why the effect occurs at low filling factor and is mainly observed in systems with predominantly repulsive scatterers. We believe that the observation of line shifts and narrowing in high-quality heterostructures with large spacers has the same origin, since there the residual p-type doping of the GaAs buffer layer determines the scattering process. Thus, these reports also support our observations. An explanation of the observed shift of the CR frequency is more difficult. In a simple model the shifted CR points to a changed energy separation between LL states. This, however, is not expected from Prange's model where the separation is exactly $\hbar\omega_c$. Mikeska and Schmidt[20] have shown that the CR of weakly bound electrons in a harmonic potential is shifted to a value $\omega^2 \simeq \omega_0^2 + \Omega^2$, where Ω is related to the curvature of the confining potential. This is in close agreement with our experiment [cf. Fig. 2(b)]. The nonoccupation of the scatterer-induced states means a spatial separation of the electrons away from the repulsive scatterers. Thus, the electrons are redistributed in "puddles" between the scatterers. The shift may, therefore, be determined by the potential which confines the electrons into the puddles.

In conclusion, we have shown specific differences in the CR of 2D EG unambiguously related to the dominant scattering type. We have proposed a mechanism for a Landau level occupation-dependent scattering, which leads to a carrier redistribution responsible for the drastic CR line narrowing and the shift observed in 2D EG's under the influence of repulsive scatterers. From our systematic investigations on well-defined systems, we believe that some of the effects seen previously bear the "fingerprint" of impurity-influenced 2D EG, even in investigations performed in high-mobility heterostructures.

We would like to acknowledge financial support from the Bundesministerium für Forschung und Technologie (BMFT).

---

[1] B. A. Wilson, S. J. Allen, Jr., and D. C. Tsui, Phys. Rev. Lett. **44**, 479 (1980).

[2] T. A. Kennedy, R. J. Wagner, B. D. McCombe, and D. C. Tsui, Phys. Rev. Lett. **35**, 1031 (1975).

[3] J. P. Kotthaus, G. Abstreiter, J. F. Koch, and R. Ranvaud, Phys. Rev. Lett. **34**, 151 (1975).

[4] B. A. Wilson, S. J. Allen, Jr., and D. C. Tsui, Phys. Rev. B **24**, 5887 (1981).

[5] Th. Englert, J. C. Maan, Ch. Uihlein, D. C. Tsui, and A. C. Gossard, Solid State Commun. **46**, 545 (1983).

[6] D. Heitmann, M. Ziesmann, and L. L. Chang, Phys. Rev. B **34**, 7463 (1986).

[7] Z. Schlesinger, S. J. Allen, J. C. M. Haug, P. M. Platzman, and N. Tzoar, Phys. Rev. B **30**, 435 (1984).

[8] Z. Schlesinger, W. I. Wang, and A. H. MacDonald, Phys. Rev. Lett. **58**, 73 (1987).

[9] F. Thiele, U. Merkt, J. P. Kotthaus, G. Lommer, F. Malcher, U. Rössler, and G. Weimann, Solid State Commun. **62**, 841 (1987).

[10] H. Sigg, D. Weiss, and K. v. Klitzing, Surf. Sci. **196**, 293 (1988).

[11] R. J. Haug, R. R. Gerhardts, K. v. Klitzing, and K. Ploog, Phys. Rev. Lett. **59**, 1349 (1987).

[12] K. Ploog, J. Cryst. Growth **81**, 304 (1987).

[13] T. Ando, J. Phys. Soc. Jpn. **38**, 989 (1975).

[14] S. Das Sarma, Phys. Rev. B **23**, 4592 (1981).

[15] R. Lassnig and E. Gornik, Solid State Commun. **47**, 959 (1983).

[16] T. Ando and Y. Murayama, J. Phys. Soc. Jpn. **54**, 1519 (1985).

[17] C. Kallin and B. I. Halperin, Phys. Rev. B **30**, 5655 (1984).

[18] H. Sigg, J. Richter, K. v. Klitzing, and K. Ploog, in *Proceedings of the Applications of High Magnetic Fields in Semiconductor Physics, Würzburg, 1988,* edited by G. Landwehr (Springer-Verlag, Berlin, in press).

[19] R. E. Prange, in *The Quantum Hall Effect,* edited by R. E. Prange and S. M. Girvin, Graduate Texts in Contemporary Physics (Springer-Verlag, Berlin, 1987), p. 14.

[20] H. J. Mikeska, and H. Schmidt, Z. Phys. B **29**, 43 (1975).