Quantum oscillation of the cyclotron mass in two-dimensional electron systems in silicon

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The cyclotron resonance of two-dimensional electron systems in silicon metal-oxide-semiconductor devices is investigated for high electron densities in high magnetic fields. The cyclotron mass, extracted from the resonance frequency, shows an oscillatory behavior. The periodicity of this oscillation is correlated with the Landau-level filling factor, with the dominant maxima of the cyclotron mass occurring at filling factors that are multiples of 4. A correlation of the oscillation amplitude with both the sample mobility and magnetic field is found. The results indicate that the observed mass oscillations result from impurity-mediated electron-electron interactions. [S0163-1829(96)07427-9]

The cyclotron resonance (CR) in two-dimensional electron systems has now been studied for over two decades.[1,2] Most of the studies have been concentrated on the CR in the extreme quantum limit, i.e., for a Landau-level filling factor $\nu = hN_s/eB \ll 1$ (where N_s is the electron density and B the magnetic field). Several remarkable features were discovered, including a shift of the CR line to higher energies in the extreme quantum limit, when only the lowest Landau level is partly filled.[3–6] For higher filling factors, an oscillatory behavior of the CR linewidth as a function of the filling factor was observed in GaAs/Al$_x$Ga$_{1-x}$As,[7] InAs/GaSb,[8] InAs/AlSb,[9] InAs/Al$_x$Ga$_{1-x}$Sb,[10] and in Ga$_{1-x}$In$_x$As/Al$_x$In$_{1-x}$As (Ref. 11) heterostructures. Furthermore, oscillations of the effective mass m_c, extracted from the CR frequency $\omega_c = eB/m_c$, have been observed in InAs/Al$_x$Ga$_{1-x}$Sb (Ref. 10) and GaAs/Al$_x$Ga$_{1-x}$As quantum wells.[12,13] So far, linewidth oscillations are mostly explained by the oscillating joint density of states[14] and screening effects[15,16] or nonparabolicity effects.[17] Oscillations in the cyclotron mass are attributed to the electron-hole interaction,[10] the collective influence of impurities[12] on the CR, or to nonparabolicity.[13]

As nonparabolicity effects play a subordinate role in silicon,[2] and in order to achieve a better understanding of the oscillations in width and position, the CR was measured on several Si-MOS (metal-oxide-semiconductor) samples fabricated on weakly p-type ($N_{\mathrm{boron}} \approx 10^{14}$ cm^{-3})-doped (100)-silicon substrates with a thermal oxide thickness of 53 nm. To study the influence of impurities, sample A was treated for 60 s in boiling, saturated NaCl solution, and sample B for 60 s in diluted NaCl solution at room temperature, whereas sample C was untreated. As a result three samples with three different peak mobilities were obtained. The two-dimensional electron system was induced via the field effect by applying a voltage V_g to a homogeneous semitransparent NiCr gate of approximately 5-nm thickness. The measurements were carried out with a far-infrared Fourier-transform spectrometer at a temperature of 4.2 K in magnetic fields up to 15 T, recording the relative change in transmission $1 - T(N_s)/T(0)$. The samples were wedged to eliminate interference effects.[1] The two-dimensional electron density N_s and the filling factor ν were determined by *in situ* measurements of Shubnikov–de Haas oscillations, employing capacitively coupled contacts.[18] However, zero-field mobilities cannot be extracted reliably with this technique. Instead, we use the observed cyclotron resonance linewidth as a measure of mobility, as discussed below.

For filling factors $1 < \nu < 4$, a splitting of the CR similar to the one reported by Cheng and McCombe[19] was observed. Whereas these phenomena at low filling factors are likely to be associated with the interplay of localization and electron-electron interaction, we concentrate in the following on studies of the metallic regime at filling factors $\nu > 4$.

For filling factors $\nu > 4$, the line shape is well approximated by a classical Lorentz profile (see Fig. 1), and therefore the cyclotron mass $m_c = eB/\omega_c$ was determined by extracting the resonance position ω_c from a Lorentzian fit. The filling factor was varied by changing the gate voltage V_g and thereby tuning the electron density N_s at a fixed magnetic field. This procedure was carried out for different magnetic fields ranging from 4 to 15 T.

In Fig. 1, the CR of sample A is plotted for different densities at fixed magnetic field $B = 10$ T. The CR frequency shows a distinct shift $\Delta\omega = \omega_c - \omega_{c,\mathrm{ref}}$ of the measured resonance position ω_c with respect to the reference value $\omega_{c,\mathrm{ref}} = eB/m_{c,\mathrm{ref}}$ ($m_{c,\mathrm{ref}} = 0.20 m_0$, where m_0 is the free-electron mass) to lower wave numbers, corresponding to a relative increase in cyclotron mass of 12%. The CR linewidth $\delta\omega$ is found to change little with electron density. We use the smallest width to determine a maximum scattering time τ_B and convert this to an equivalent peak mobility μ_p corresponding to Abstreiter *et al.*[1] For sample A we obtain $\mu_p = 0.55$ m^2/V s. The oscillation of the cyclotron mass can be seen more clearly in sample B ($\mu_p = 0.85$ m^2/V s) in Fig. 2. Again the linewidth stays almost constant over the whole density range. The fitting error of the cyclotron mass is within the size of the square symbols. For sample B the maximal shift of the cyclotron frequency corresponds to a relative increase of the cyclotron mass of 6%. Prominent maxima occur at filling factors $\nu = 4n$, with n being a posi-

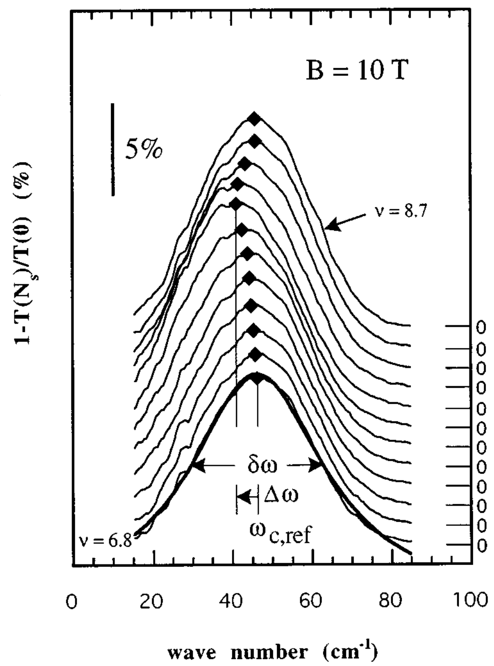

FIG. 1. Infrared transmission spectra of the CR at $B=10$ T (sample A: $\mu=0.55$ m^2/V s). The electron density N_s is varied in equidistant steps between 1.64×10^{12} cm^{-2} (lower curve) and 2.10×10^{12} cm^{-2} (upper curve), corresponding to filling factors between $\nu=6.8$ and 8.7. The CR traces are offset for clarity. The data show that the linewidth $\delta\omega$ remains almost constant, whereas a clear shift $\Delta\omega$ in resonance position is observable, which is maximal around $\nu=8$.

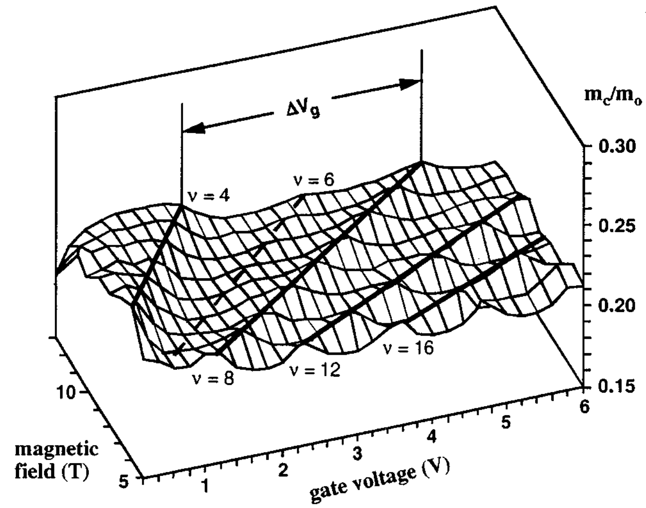

FIG. 3. Three-dimensional plot of the cyclotron mass with respect to the free-electron mass as a function of gate voltage and magnetic field (sample B: $\mu=0.85$ m^2/V s).

tive integer. Due to the twofold spin and valley degeneracy on silicon (100), the filling factors $\nu=4n$ correspond to completely filled Landau levels. In addition, maxima appear at filling factors $\nu=4n+2$, showing that the spin degeneracy is lifted. Even at filling factors $\nu=2n+1$ weak maxima are discernible, corresponding to the lifting of the valley degeneracy. Both the lifting of the valley as well as the spin degeneracy are only observed at high magnetic fields. The slight increase of the baseline, which connects the minima of the cyclotron mass for electron densities between 2×10^{16} and 4×10^{16} m^{-2}, as indicated by the dashed line, is interpreted as nonparabolicity of the conduction-band edge in silicon. This effect has been predicted by Falicov[20] and verified by Theis[21] and Stallhofer[22] in earlier measurements. They observed an increase of 2% in this density regime, which is in very good agreement with our data.

In Fig. 3 the same cyclotron mass oscillations of sample B are shown for several magnetic fields and gate voltages simultaneously. Some features should be noted. The dominant maxima of the cyclotron mass appear at filling factors $\nu=4n$, independent of the magnetic field. The amplitude, however, decreases at higher magnetic fields. Due to the scale in this picture, only the spin splitting can be seen for high magnetic fields, whereas the valley splitting is not visible even at high magnetic fields.

As shown in Fig. 4, the period ΔV_g of the cyclotron mass oscillations in gate voltage as a function of the magnetic field

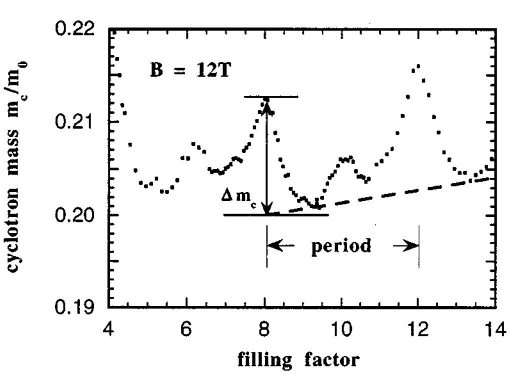

FIG. 2. Oscillation of the cyclotron mass with respect to the free-electron mass as a function of filling factor at $B=12$ T (sample B: $\mu=0.85$ m^2/V s). The increase of the baseline in the density regime between 2×10^{16} and 4×10^{16} m^{-2} is indicated by the dashed line.

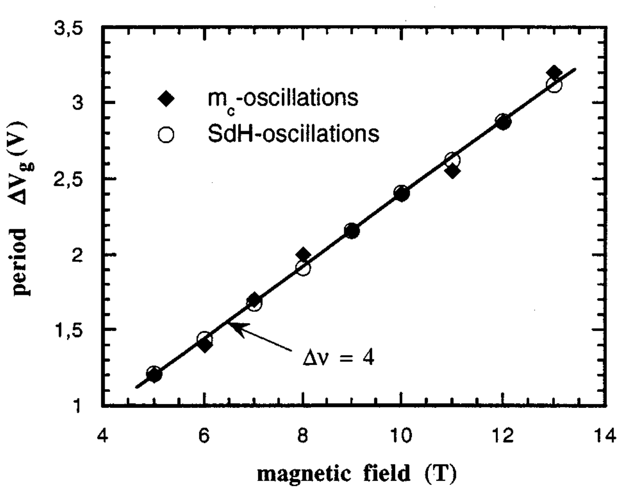

FIG. 4. Gate voltage period ΔV_g at fixed magnetic fields of the dominant oscillations of the cyclotron mass m_c and Shubnikov–de Haas oscillations vs magnetic field. The slope of the linear fit corresponds to $\Delta\nu=4$ (sample B: $\mu=0.85$ m^2/V s).

TABLE I. Peak mobility μ_p and scattering time τ_B at $B=12$ T, and the relative increase of the mass in units of the reference mass $0.2m_0$ of samples *A*, *B*, and *C*.

	μ_p (m^2/V s)	τ_B ($B=12$ T) (ps)	$\Delta m_c/0.2m_0$
Sample *A*	0.55	0.33	0.12
Sample *B*	0.85	0.51	0.06
Sample *C*	1.30	0.70	0.03

corresponds exactly to $\Delta\nu=4$ (see also Figs. 2 and 3). The agreement with the periodicity of the Shubnikov–de Haas oscillations (N_s sweep, B=const) is excellent. More exact measurements have shown that within an accuracy of 3% the main maxima of the cyclotron mass coincide with the filling factors $\nu=4n$, reflecting completely filled Landau levels. These results have been verified on different samples with different peak mobilities μ_p, ranging from 0.55 to 1.3 m^2/V s.

The experiments also demonstrate that the amplitude of the oscillation depends on both the magnetic field and the electron peak mobility μ_p of the sample. With increasing magnetic field as well as with higher mobility (different samples), i.e., with increasing $\omega_c\tau$, the amplitude of the cyclotron mass oscillation Δm_c, as defined in Fig. 2, decreases as exemplified in Table I.

Assuming a Gaussian scattering potential, Ando[14] has predicted that the oscillating joint density of states causes oscillations of the CR frequency with an amplitude that is highest for short-range scatterers. However, in Ando's model these quantum oscillations of the CR frequency are accompanied by a corresponding linewidth oscillation, which is not observed here. The well-known Kohn theorem[23] states that in a homogeneous translationally invariant system, electron-electron interactions do not influence the CR mass. However, as pointed out by Tzoar, Platzman, and Simons,[24] scattering by impurities is able to break the translational invariance and reintroduces electron-electron interactions into the CR frequency. In particular, one expects that the role of electron-electron interaction increases with increasing impurity concentration, and hence decreasing $\omega_c\tau$ in qualitative agreement with the observations presented here. Subsequent more detailed calculations by Gold[25] that include the role of a finite magnetic field as well as surface roughness scattering qualitatively support the predictions by Tzoar, Platzman, and Simons, but do not include Landau-level quantization. Self-consistent calculations of the CR in quantizing magnetic fields, carried out by Kallin and Halperin,[26] which take into account the electron-impurity and the electron-electron interaction, show a shift of the CR to lower frequencies for both short- as well as long-range scatterers under the assumption of high magnetic fields and completely filled Landau levels ($n=1,2,\ldots$). They predict the CR peak to be broadened/not broadened in the case of long-range/short-range scatterers. However, none of these calculations includes a filling-factor-dependent screening of the long-range impurity scattering, which we believe is essential to explain the mass oscillation observed here. Long-range Coulomb scatterers are substantially screened whenever a Landau level is half-filled, whereas the diminished electron density of states between Landau levels strongly suppresses screening whenever the filling factor ν becomes an integer. This suppression will be particularly strong at filling factors $\nu=4n$ ($n=1,2,\ldots$), i.e., when the Fermi level lies between distinct Landau levels n.[16]

Our exeriments indicate that the filling-factor-dependent screening of long-range scatterers modulates the strength with which the electron-electron interaction is reintroduced into the CR mass via the presence of impurities. Thus samples with more long-range impurities (*A*,*B*) show stronger oscillations. The magnetic-field dependence of the amplitude of the cyclotron mass oscillation can be explained qualitatively. The radius of the cyclotron orbit decreases with increasing magnetic field, so that the influence of long-range Coulombic scatterers on the electron gas becomes negligible on that scale at high magnetic fields. The absence of discernible concomitant linewidth oscillations that is difficult to explained within a single-particle model may possibly reflect the action of electron-electron interaction on the CR that can yield a collective resonance not inhomogeneously broadened.[27]

It should be noted that experiments with similar oscillations of the cyclotron mass in InAs/Al_xGa_{1-x}Sb (Ref. 10) and GaAs/Al_xGa_{1-x}As heterostructures[12,13] are associated with more or less pronounced oscillations in linewidth. On InAs, however, only an oscillation in linewidth, but no oscillation of the cyclotron mass, was observed by Heitmann, Ziesmann, and Chang.[8] In all these cited experiments the filling factors are varied by adjusting the magnetic field for a given electron density. The results pressented here in Fig. 3 show that the oscillations occur independently of the method of varying the filling factor.

Therefore, the oscillatory behavior seems to be a general feature of two-dimensional-electron systems. The details, whether the oscillations occur only in the cyclotron mass or only in the linewidth, or in both, depend on the sample-dependent scattering mechanism, via which electron-electron interactions are reintroduced into cyclotron resonance. In samples with a strong nonparabolic conduction band (InAs) one also has to consider the dependence of the bare band-structure mass on the Landau-level filling factor, a complication avoided here.

In summary, we have investigated the filling-factor dependence of the cyclotron mass in Si-MOS structures for $\nu>4$, which exhibits an oscillatory behavior. The cyclotron mass enhancement is strongest at integer filling factors $\nu=4n$, when screening of long-range Coulombic scatterers is expected to be least effective.[16] The period of the cyclotron mass oscillation is $\Delta\nu=4$. Maxima occur at integer filling factors, main maxima at filled Landau levels.

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