Anomalies in the Cyclotron Resonance of Quasi-Two-Dimensional Electrons in Silicon at Low Electron Densities

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Systematic line-shape studies of the "anomalous" cyclotron resonance of quasi-two-dimensional electrons in Si metal-oxide-semiconductor devices at low temperature and low densities have revealed a *multiple-line structure*. The ratio of electron density to magnetic field (Landau-level filling factor) at which the anomalies appear is systematically correlated with the inverse of the electron peak effective mobility, demonstrating the importance of localization. Several features cannot be explained by single-particle localization, and it is argued that electron-electron correlations also play an important role.

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Cyclotron resonance (CR) is a fundamental measurement in the study of the dynamical properties of quasi-two-dimensional (2D) electronic systems. In principle, the quantum-limit condition, when all electrons are in the lowest Landau level, provides the simplest situation for understanding the line shape. However, at extremely low densities and high magnetic fields, the resonance shows numerous "anomalies." Extensive experimental investigations have been carried out on various quasi-2D electronic systems with results interpreted by a variety of theoretical models. Previous work on inversion layers in Si led to several theoretical interpretations.[1-6] Recent work on GaAs/AlGaAs heterostructures has revealed additional features and produced additional theoretical models.[7-14] At present, in spite of considerable effort none of these theoretical models is completely established, and there is not yet a clear physical picture that unifies all of the anomalies observed in various low-density CR experiments.

We have carried out a systematic experimental investigation of cyclotron resonance at low temperatures and low electron densities on a series of Si metal-oxide-semiconductor field-effect–transistor samples having a wide range of peak effective mobilities.[15] These data exhibit a single CR line at high densities, a clear *multiple-line structure* in a crossover region of intermediate densities, and a sharp line at very low densities that is shifted to high frequencies by an amount that correlates inversely with the sample peak mobility. The effects of magnetic field, temperature, substrate bias, and surface band structure on these characteristics have been investigated. The observation of a multiple-line structure, unrelated to population of higher valleys in the Si conduction band, and correlation of the magnitude of the anomalies with the inverse of the sample mobility provide a new perspective on this problem.

All samples used in these studies have semitransparent chromium gates (area 2.5×2.5 mm^2) and oxide thicknesses near 2000 Å with peak effective mobilities between 4500 and >10000 cm^2/Vsec at 4.2 K. Sample surfaces were oriented vicinally to the (100) direction with the largest tilt angle equal to 10°: sample 1, 4500 cm^2/Vsec, (100); sample 2, 5600 cm^2/Vsec, (100); sample 3, 7000 cm^2/Vsec, (811); and sample 4, >10000 cm^2/Vsec, 1° tilted from (100). Low-frequency (<100 Hz) gate-modulation measurements were carried out at temperatures between 2.2 and 30 K with a far-infrared Fourier-transform spectrometer, 9- and 15-T superconducting magnets, and a Si-composite bolometer detector. The electron density n_s was obtained from the gate voltage V_G above threshold with the n_s-V_G relation and threshold voltage determined from Shubnikov–de Haas oscillations at 4.2 K each time the sample was cooled down.

Figures 1(a)–1(d) show the density dependence of the electron CR line shape for four samples at 9 T and 4.2 K. At high electron densities, or equivalently large Landau-level filling factors ν ($\nu = hcn_s/eB$, where n_s is the 2D electron density) at fixed magnetic field, CR is a single, symmetric, and reasonably sharp line with linewidth inversely proportional to sample mobility. The resonance shifts slightly to lower frequency as ν is reduced to a critical value ν_c, which varies from 3 to 1 between the lowest- and highest-mobility samples. Dramatic changes in line shape occur near ν_c; a new feature appears (initially as a shoulder) on the high-frequency side of CR which causes the line to be asymmetric when it is not well resolved. As ν is reduced further, a multiple-line structure is clearly resolved in the poorer-mobility samples, and the overall linewidth becomes *extremely* large. The relative intensities of the lower-frequency peaks decrease rapidly as density is reduced; thus the overall linewidth dramatically narrows, and the center of gravity (defined operationally as the frequency for which the integrated intensity above is equal to that below this frequency) moves quickly to the position of the high-frequency line. At the lowest ν ($\nu < 0.4$–1.3 between the highest- and lowest-mobility samples), the highest-frequency peak becomes the dominant line with linewidth significantly narrower than that

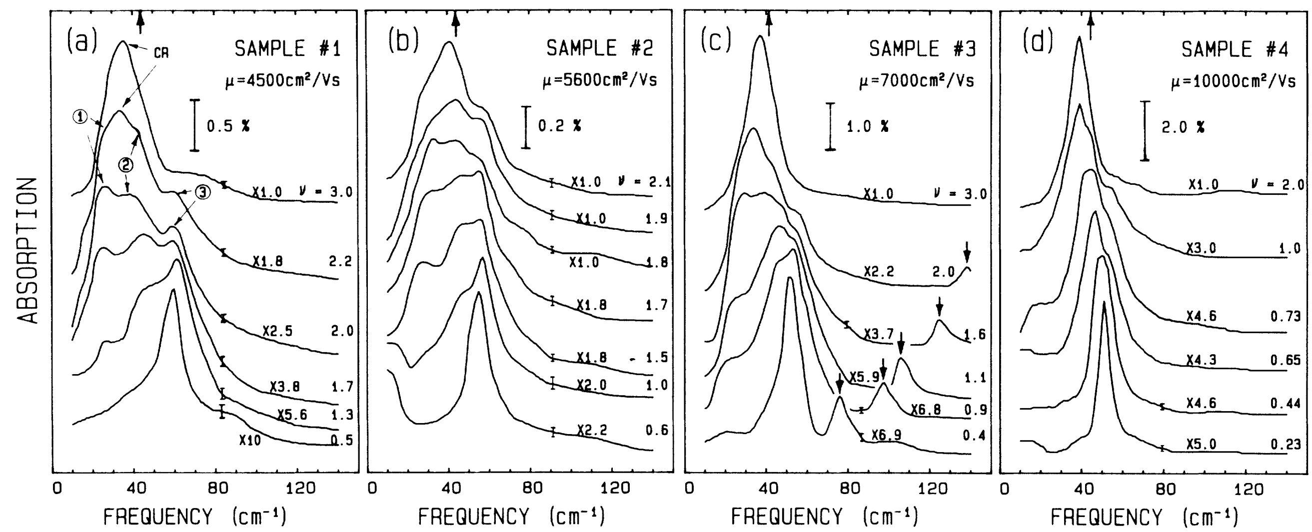

FIG. 1. Filling-factor (ν) dependences of CR line shape for four samples at 9 T and 4.2 K. Bars indicate the noise level. An arrow at the top of each panel is the position of unperturbed CR defined by the bulk cyclotron mass for the twofold valleys. Features indicated by arrows in (c) are intersubband transitions due to surface tilt.

of the high-density CR line. It shifts slightly to lower frequency as ν is reduced further. In this region, the linewidth exhibits only a weak sample dependence (full width at half maximum $\sim$8–10 cm^{-1} between the highest- and lowest-mobility samples). It is apparent that lower-mobility samples show clearer multiple-line structure, but the general features for all samples are similar. Varying the surface crystallographic plane has no discernible effect. For the samples with surfaces substantially tilted ($\simeq 10°$) from (100), intersubband transitions can be observed [arrows in Fig. 1(c)] due to the anisotropic energy surfaces of silicon.[16]

The evolution in intensity and frequency of these lines with ν for sample 1 is shown in Figs. 1(a) and 2(a). As ν is reduced the relative intensity of CR decreases and three additional lines appear [labeled 1, 2, and 3 in Figs. 1(a) and 2(a)]. Lines 1 and 2 are observable only in a narrow range ($1.3 \lesssim \nu \lesssim 2.5$) with line 1 shifting down and line 2 shifting up, whereas line 3 is first observable as a high-frequency shoulder near $\nu = 3$ and increases in relative intensity with no dramatic frequency shift all the way down to the lowest values of ν. Very similar behavior is observed for the two intermediate-mobility samples (2 and 3) at progressively lower filling factors. In the highest-mobility sample only CR and line 3 are clearly observed with line 3 first appearing as a shoulder at $\nu \simeq 1$ and becoming the dominant, sharp feature below $\nu \simeq 0.4$. There is some indication of line 2 between $\nu = 1$ and 0.4 in Fig. 1(d), but it is not clearly resolved. There is no clear indication of line 1 in this sample.

In Fig. 2(b), the center of gravity of the multiple-line structure is plotted as a function of ν for all samples at 9 T. At the high and the lowest values of ν, the center of gravity is the position of CR and of line 3, respectively, since only a single line appears in these regions. At intermediate values of ν, it is the frequency most likely to be chosen as the "CR" position when the multiple-line structure is not well resolved; thus it can be used to compare with the early work (e.g., Ref. 3). The frequency shift of the absorption peak at the lowest densities from the unperturbed CR position (defined by bulk cyclotron mass) increases systematically from about 6 to 15 cm^{-1} between the highest- and lowest-mobility samples. The systematic mobility dependence of ν_c, i.e., a continual reduction in ν_c as mobility increases, is apparent. Figure 2(c) shows the ν dependence of the peak position relative to the unperturbed CR position for one sample at three magnetic fields. The qualitative behavior is unchanged over this range of magnetic fields, demonstrating that the filling factor, not n_s, is the parameter that correlates with line shape for a given sample within experimental error.

Although the dependence of the center of gravity and the overall linewidth on ν appear similar to earlier work on Si,[2,3] the detailed results are *quite different*. First, the anomalous behavior of low-density "cyclotron resonance" is due to the appearance of multiple components (3–4) within the overall line profile near ν_c, with relative intensities varying strongly with filling factor. Very recent work on modulation-doped GaAs/AlGaAs heterostructures with additionally doped Be acceptors in the GaAs near the interface show a *double*-line structure with similar qualitative behavior.[17] Second, the filling-factor dependence of the line shape is *not strict* as suggested by earlier work; both detailed line shape and ν_c depend on sample mobility. However, for a given sample, the filling factor is indeed the parameter that correlates with line shape [Fig. 2(c)]. Third, the magnitude of the anomalies increases systematically with decreasing

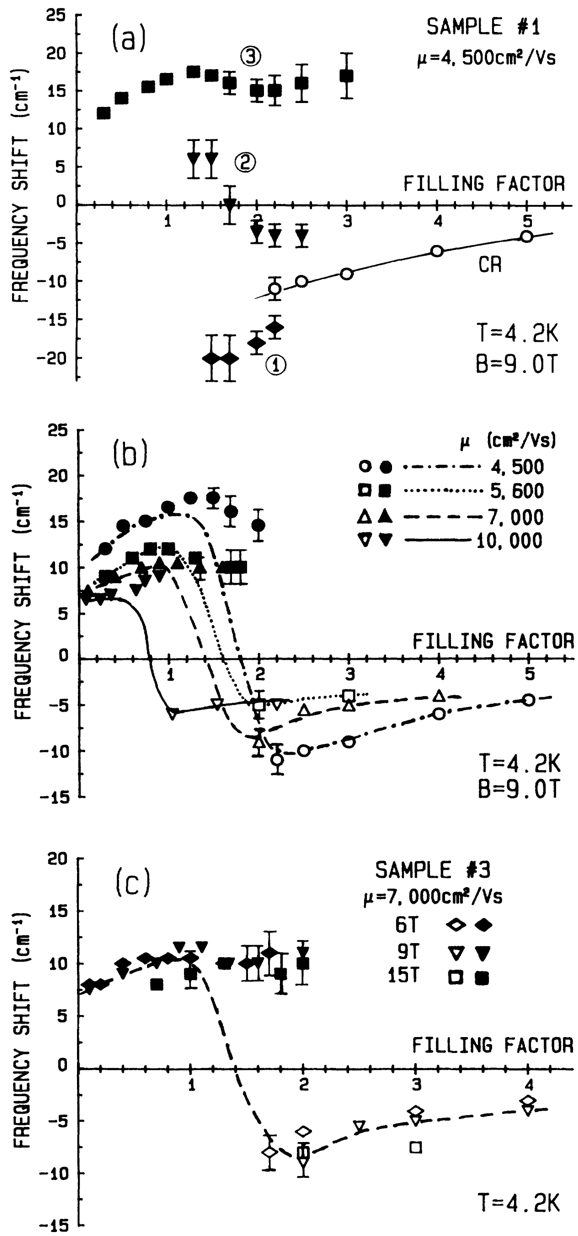

FIG. 2. Peak position shift from unperturbed CR as a function of ν. (a) Evolution of multiple-line structure for sample 1. (b) The center of gravity of the complex line for four samples. Open symbols: CR positions at high ν; solid symbols: positions of the sharp line at the lowest values of ν. (c) Sample 3 at three magnetic fields. The broken line is the center of gravity at 9 T.

mobility; i.e., poorer-mobility samples have higher ν_c, clearer multiple-line structure, and larger frequency shift from the unperturbed CR position at the lowest values of ν.

Temperature- and substrate-bias-dependent measurements have shown that the band tails associated with the fourfold-degenerate higher-lying valleys, which extend well below the mobility edge,[18] can be thermally populated at rather low temperature. At the lowest ν, a low-frequency sharp line is observed on samples 3 and 4 at elevated temperatures ($\sim$25 K), and it rapidly disappears for small reversed substrate bias. This line, associated with the fourfold valleys, shows slightly larger frequency up-shift in comparison with twofold valleys. For large reverse substrate bias, the sharp line (associated with twofold valleys) at the lowest ν moves to slightly higher frequency, and linewidth increases, consistent with an increase in the strength of the random localization potentials as $\langle z \rangle$ decreases.[3]

The systematic mobility dependence of the various features clearly demonstrates the importance of localization. In a single-particle localization model[4] random potential fluctuations at the interface have been treated approximately by introducing a limited set of finite harmonic-oscillator potentials with different characteristic frequencies ω_0. For electrons confined in such oscillator potentials the allowed dipole transitions in the presence of a uniform external magnetic field normal to the interface occur at frequencies given by

$$\omega_\pm = \tfrac{1}{2}\,[(\omega_c^2+4\omega_0^2)^{1/2} \pm \omega_c]\,,$$

where ω_+ represents the shifted cyclotron frequency, and ω_- is the frequency of anticyclotron motion of the orbit center due to the scattering from the potential walls. Despite its simplicity this model can explain qualitatively the mobility-dependent frequency up-shift at low densities, the larger frequency shift for fourfold valleys (smaller ω_c), and the substrate-bias results (reverse substrate bias increases ω_0). However, several important experimental facts cannot be explained by this model: (i) The sharpness of the line at the lowest values of ν. The line should be inhomogeneously broadened by the distribution of random potentials (harmonic-oscillator potentials). (ii) The multiple (3–4) line structure near ν_c. This model yields, at most, *two* lines in addition to CR, and the lower branch occurs at too low a frequency at the fields used in these experiments to be detected; it is significantly lower than line 1 discussed above. (iii) The ν-dependent behavior for a given sample. The model predicts that the electron density, not ν, is the critical parameter determining the line shape. The *ad hoc* addition of screening, which has maximum effect at half-integral ν, and which would reduce the shift and linewidth at these values, cannot explain either the gradual monotonic decrease in frequency shift below $\nu \simeq 1$ for all samples, or the initial appearance of the narrowed line at different ν for different samples.

Electron-electron interaction is one of the dominant energies in this problem. The Coulomb repulsion of two electrons localized in the same potential well (200 Å diam) is approximately 6 meV, considerably greater than the typical magnitude of the fluctuating potential. Thus, single electrons will tend to be localized in individual potentials. If we allow a pair of such electrons to interact, and treat this interaction as a perturbation on their single-particle states, the result is to increase confinement and transition energies, with the largest shift occurring for the weakest potential (smallest ω_0). As a result, Coulomb repulsion shifts the frequencies of all the single-particle potentials upward and *narrows* any inhomogeneously broadened line profile, in qualitative agreement with the low-density observations.

The multiple-line structure and the variation of the relative intensity of each component with ν are not predicted either by the single-particle localization model or by existing many-body calculations. We suggest that spin-valley splitting of the Landau levels coupled with electron correlations is a possible explanation; the electron-exchange interaction greatly enhances the spin-valley splitting and couples the spin and valley states.[19] The magnitude of the exchange energy depends on Landau-level occupancy (ν), and is largest for the lowest Landau level. Coupled valley states with separation dependent on ν could lead to a multiple-line structure for $\nu < 4$. However, the dependence on mobility is not obvious; there are no calculations for the exchange effects for electrons localized in random potentials in high magnetic fields to the best of our knowledge. The "discrepancy" between the number of components observed in the present experiments and those of Ref. 17 is understandable in this context since there is no valley degeneracy in GaAs. It is apparent that both localization and many-body interaction are required in order to understand the low-density cyclotron resonance; the relative importance depends on the quality of the structures investigated.

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