Dynamical Conductivity of the GaAs Two-Dimensional Electron Gas at Low Temperature and Carrier Density

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We use infrared cyclotron-resonance measurements to study the dynamical conductivity of a gated GaAs two-dimensional electron gas in a perpendicular magnetic field in the regime of low carrier density and temperature where electron correlation and exchange effects are most important. For $T \simeq 0.4$ K the resonance narrows and shifts dramatically as the density is reduced below the point at which the lowest spin-split Landau level is filled. This observation provides the first demonstration of a strong influence of electron-electron interactions on the cyclotron-resonance line shape.

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Two-dimensional electron structures provide excellent model systems in which to test our understanding of the behavior of interacting electrons at low temperature, particularly when the areal carrier density can be varied.[1] Phenomena ranging from classical Wigner crystallization[1] and fractional Landau-level quantization[2] to Anderson localization[1] have been studied. In the GaAs/(GaAl)As two-dimensional electron gas (2DEG), high electron mobilities are obtained at degenerate densities; thus there is a strong electron-electron interaction and only a modest amount of disorder. The electronic behavior of this system should be quite interesting at low temperature, particularly in the presence of a large perpendicular magnetic field which overwhelms the Fermi degeneracy.[1-3]

Cyclotron resonance is a probe of fundamental significance because it can be used to measure directly the dynamical (i.e., finite frequency) conductivity of the 2DEG in a perpendicular magnetic field.[1] In the Si MOSFET (metal-oxide-semiconductor field-effect transistor) 2DEG a narrowing and shift of the conductivity resonance has been observed at low carrier density and temperature; its explanation in terms of charge-density-wave pinning remains controversial.[1] The modulation-doped 2DEG in GaAs provides a much less disordered system in which to study the behavior of $\sigma(\omega)$. Previous cyclotron-resonance measurements in this system at moderate and high 2D electron density n, however, have produced a confusing array of apparently contradictory or sample-dependent results.[4-9] Englert *et al.*[4] observed linewidth maxima at certain even-integer filling factors, while line splittings and maxima occurring at noninteger filling factor were subsequently reported.[6] In these experiments changing n has meant changing the sample; hence systematic study of density dependence of the most interesting phenomena has not been possible. In this Letter we concentrate on the low-density regime, in which the relationship between cyclotron resonance and dynamical conductivity is most immediate, and use a backgate to vary n by an order of magnitude controllably and reproducibly. For $T \simeq 0.4$ K the conductivity resonance narrows and shifts dramatically as the density is reduced below the point at which the lowest spin-split Landau level is filled. We argue that this behavior demonstrates the importance of electron-electron interactions in the determination of the cyclotron-resonance line shapes in our samples.

The samples used in these experiments are grown by molecular-beam epitaxy on the B face of (311)-oriented GaAs substrates.[10] The 2DEG forms at the interface of undoped GaAs and (GaAl)As. The setback distance to the Si-doped (GaAl)As region is more than 500 Å for each of our samples. With use of diamond laps, the sample is thinned to about 50–150 μm and placed on a wedged ($\sim 2°$) sapphire substrate with a transparent Nichrome gate ($R_\square \gtrsim 5$ kΩ). This backgated 2DEG is then mounted in a top-loading ^{3}He immersion cryostat with axial infrared access where it can be studied from 0.3 to $\gtrsim 70$ K in perpendicular magnetic fields up to 14 T. Radiation from either a laser or a broadband interferometer source is transmitted through the sample at normal incidence and detected by a bolometer below the strong-field region. dc magnetotransport measurements show the usual minima in σ_{xx} at appropriate integer and fractional filling factors at low temperature,[2] and are used together with the integrated areas from the infrared conductivity resonance measurements to establish the 2D carrier density at different gate voltages.

The relationship between the transmission and the dynamical conductivity, $\sigma(\omega;B)$, is given by[1]

$$\frac{T_0^+}{T^+}=\frac{|Y_1+Y_2+\sigma(\omega;B)|^2}{|Y_1+Y_2|^2} \quad (1)$$

in the absence of multiple reflections, where T^+ and T_0^+ are the circularly polarized transmission and reference spectra, and $Y_1=\frac{1}{377}\ \Omega$ and $Y_2\simeq\frac{3.4}{377}\ \Omega$ are the respective admittances of free space and GaAs. In the absence of a magnetic field the conductivity resonance of a metallic system is peaked at zero frequency. A perpendicular magnetic field shifts the 2DEG conductivity resonance to the finite frequency $\omega_c=eB/m^*c$. In a Drude-type model,

$$\sigma(\omega;B)=\sigma_0/[1+i(\omega-\omega_c)\tau], \quad (2)$$

in which case one obtains from Eq. (1)

$$\tilde{\sigma}\equiv T_0^+/T^+-1 = \frac{2}{Y_1+Y_2}\left[1+\frac{\sigma_0}{2(Y_1+Y_2)}\right]\mathrm{Re}\,\sigma(\omega;B). \quad (3)$$

Linewidths obtained from data plotted in this way will thus tend to be undistorted by systematic dependence on n and will accurately reflect the width of the conductivity resonance. All linewidths mentioned here are the full width at half maximum of $\tilde{\sigma}$ (i.e., $\sim 2/\tau$).

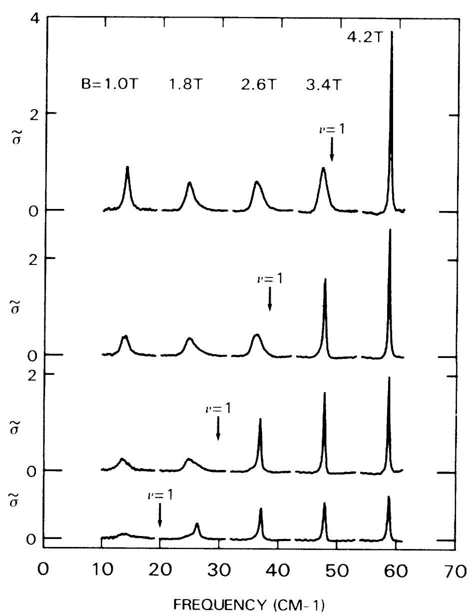

FIG. 1. The reduced dynamical conductivity, $\tilde{\sigma}$, at 0.4 K is plotted as a function of frequency for perpendicular magnetic fields as indicated. From top to bottom, the areal carrier densities are estimated to be $(0.8, 0.65, 0.5, 0.35)\times 10^{11}$ cm^{-2}, with an accuracy of about $0.05\pm 10\%$. The cyclotron frequency at which $\nu=1$ is indicated by the arrow for each density.

We have studied cyclotron resonance in our gated samples in fields up to 14 T at 0.4 K and although we observe deep minima in our dc σ_{xx} at $\nu=\frac{1}{3}$ and $\frac{2}{3}$ we do not find any change in either the cyclotron frequency[11] or linewidth[7,12] correlated with these fractional fillings. However, sudden changes do occur near $\nu=1$ as we describe in the following.

In Fig. 1 we show broadband interferometer measurements of $\tilde{\sigma}$ as a function of frequency at $T\simeq 0.4$ K. We observe that upon our reducing n or increasing B the resonance narrows abruptly at a filling factor just below $\nu\simeq 1$ (i.e., where the lowest spin-split Landau level is full). It also appears that the integrated area of the conductivity resonance drops by roughly 10% below $\nu\simeq 1$.

In Figs. 2(a) and 2(b) we show swept-field measurements of $\tilde{\sigma}$ at 0.4 K at fixed laser frequency [25.4 cm^{-1}

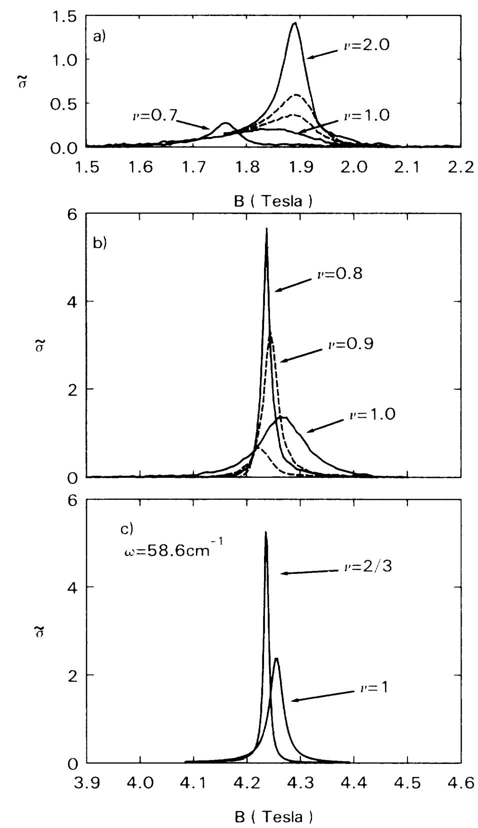

FIG. 2. Swept-field cyclotron-resonance data at $T=0.4$ K are shown in terms of $\tilde{\sigma}$ for laser frequencies of (a) 25.4 cm^{-1} and (b) 58.6 cm^{-1}. The unlabeled dashed curves in (a) are at $\nu=1.7$ and 1.3, and in (b) at $\nu=0.3$. The $\tilde{\sigma}$ curves in (c) are based on the theory outlined in the text with the disorder scattering due to ionized impurities set back back between 25 and 35 nm from the 2DEG. The narrowing which occurs between $\nu=1$ ($n=1\times 10^{11}$ cm^{-2}) and $\nu=\frac{2}{3}$ ($n=\frac{2}{3}\times 10^{11}$ cm^{-2}) is despite a dc mobility lower by a factor of 2 at the lower density. In each case the undressed resonance occurs at $B=4.19$ T.

in 2(a) and 58.6 cm^{-1} in 2(b)] for several values of the 2D carrier density, n. {At $\nu \simeq 0.8$ [Fig. 2(b)] the linewidth (0.012 T$\simeq$0.17 cm^{-1}) is about eight times more narrow than the corresponding conductivity resonance width at $B=0$ as deduced from the dc mobility, $\mu \simeq 1.8\times10^5$ $cm^2/V\cdot s$. For a system, such as the GaAs 2DEG, dominated by long-range scattering, there is no simple relationship between the dc mobility and the cyclotron (i.e., finite-frequency conductivity) resonance linewidth.[3,13]} Figure 2(c) shows the behavior expected for $\tilde{\sigma}$ near $\nu=1$ on the basis of a theory which we describe below. It is apparent in Figs. 2(a) and 2(b) that the linewidth narrowing for $\nu<1$ is accompanied by a substantial downward (upward) shift of the resonant field (frequency). At the lower laser frequency the narrowing is less dramatic, and the shift is larger.

In Fig. 3, we show the temperature dependence of the resonance field and linewidth [full width at half maximum of $\tilde{\sigma}$; see Eq. (3)]. The gradual increase of B_c for $T>10$ K persists to rather high temperature ($T>60$ K), which may suggest a phonon- or band-structure–related mechanism for this behavior. In this Letter we focus our attention on the lower temperature regime, in which B_c increases abruptly for $\nu=1$ but not for $\nu=0.7$, and the linewidth broadens for $\nu=1$ while narrowing for $\nu=0.7$.

In a previous study of cyclotron resonance in the GaAs 2DEG Englert *et al.*[4] have observed linewidth maxima at $\nu\simeq2$ and $\nu\simeq4$. Linewidth oscillations with maxima at even integral values of ν[1,4,14] seem to be well described by theories which reflect the absence of a contribution to screening from intra-Landau-level excitations whenever a Landau level is full.[15-17] When the exchange enhancement of the g factor is sufficiently large, or the Landau-level broadening sufficiently weak for the Landau level to be spin split, the same effect should produce linewidth maxima at odd integral values of ν. In our observations the linewidth increases dramatically as ν approaches unity from below; however, the linewidths are smaller than would be expected from the above theories and the broadening is systematically associated with an upward shift of the resonant field. Such an association is present in the theory of Kallin and Halperin[3] (KH) and we believe that our data provide the first convincing evidence for the profound influence of electron-electron interactions on cyclotron resonance which they predicted for systems with sufficiently weak disorder.

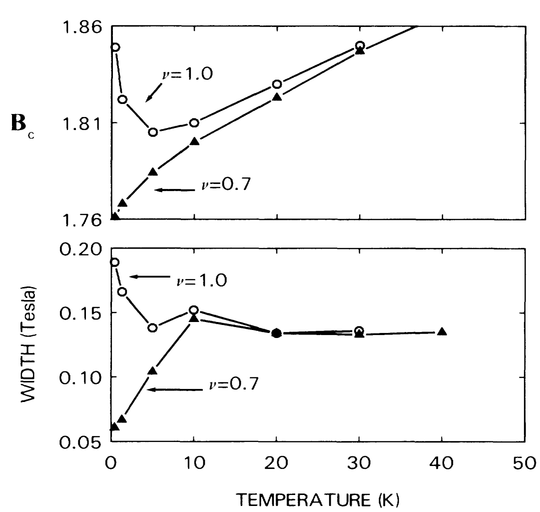

FIG. 3. The temperature dependence of the resonant field and linewidth at the laser frequency 25.4 cm^{-1} are shown for $\nu\simeq0.7$ and 1.0. The resonance at $\nu\simeq1.0$ shifts upward abruptly and broadens at low temperature.

The KH theory applies only for integral values of ν and is based on the observation that, without disorder, the states with excitation energies near $\hbar\omega_c$, $|\psi_{\mathbf{k}}^{mp}\rangle$ (the magnetoplasmons), are shifted upward by Coulomb interactions[3,18] by an amount which goes to zero as $|\mathbf{k}|\rightarrow0$. With disorder these modes are coupled and the cyclotron resonance signal is the projection of their density of states onto $|\psi_{\mathbf{k}=0}^{mp}\rangle$. Because of level repulsion the Coulomb interaction, which appears in the magnetoplasmon dispersion, causes the cyclotron resonance position to shift to lower frequencies and, by lifting the degeneracy of the magnetoplasmon modes, reduces the broadening. For $\nu\neq1$, the magnetoplasmon modes are not exact eigenstates of the disorder-free Hamiltonian but are expected to be well-defined collective modes. Their dispersion relation has been evaluated[19] and the matrix elements of the disorder potential can be expressed in terms of ground-state correlation functions.[20] In the regime where the fractional quantum Hall effect occurs, the intra-Landau-level contribution to static screening can be accurately approximated.[21,22] In the KH theory, the screening which appears for $\nu<1$ reduces the coupling of magnetoplasmon modes so that the downward shift of the cyclotron frequency and the linewidth are reduced together, as in our data. The results illustrated in Fig. 2(c) are based on the generalization of the KH theory to $\nu<1$ outlined above. The degree of linewidth narrowing is, on a quantitative level, sensitive to the model used for the disorder potential, but the qualitative aspects emphasized above are a generic property of the theory.

Although the calculation is only for $T=0$ one can qualitatively understand the temperature dependence exhibited in Fig. 3 as follows. At $\nu=1$, the 2DEG loses its ability to screen at very low temperature, because a large gap opens up at the Fermi surface as a result of the exchange-enhanced spin splitting of the Landau level. The consequence of this is that the interaction between the cyclotron mode (at ω_c) and the finite-wavelength magnetoplasmons (at $\omega>\omega_c$) becomes dramatically stronger since the impurity potential which mediates the interaction is no longer effectively screened. The level repulsion then broadens the resonance and depresses the resonance frequency, thus producing the upward shift of B_c and the increase in width observed in Fig. 3 for $\nu=1$ at low T. For $\nu<1$, on the other hand, screening simply becomes more effective at low temperature which leads to the linewidth narrowing shown in Fig. 3.

This temperature dependence is actually quite different from the expected signature of charge-density-wave (CDW) pinning, which has been suggested as the mechanism responsible for similar behavior observed in the Si MOSFET 2DEG.[23] In that picture one expects that for $\nu<1$ B_c should decrease as the 2DEG is cooled below a transition temperature, whereas at $\nu=1$ nothing much should happen because the CDW ground state is supressed. In contrast, we observe primarily an increase in B_c for $\nu=1$ at low T, while for $\nu<1$ B_c does not depart dramatically from its higher-temperature behavior. This temperature dependence thus provides an experimental basis upon which to distinguish the between the pinned-CDW model and the magnetoplasmon interaction model presented here. The inability of simpler one-electron models to account for the data has been dealt with effectively in Ref. 23.

In conclusion, over a wide range of 2D carrier density we observe a narrowing and shift of the dynamical conductivity resonance which occurs as the filling factor is reduced below 1. We show that this behavior is expected in the regime in which the electron-electron interaction is stronger than the disorder potential. It is due to a combination of the upward shift from $\hbar\omega_c$ of the finite-wave-vector magnetoplasmons due to electron-electron interactions, and the filling-factor dependence of the screening from intra-Landau-level excitations.

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[1]T. Ando, A. B. Fowler, and F. Stern, Rev. Mod. Phys. **54**, 437 (1981).

[2]D. C. Tsui, H. L. Stormer, and A. C. Gossard, Phys. Rev. Lett. **48**, 1559 (1981).

[3]C. Kallin and B. I. Halperin, Phys. Rev. B **31**, 3635 (1985).

[4]Th. Englert, J. C. Maan, Ch. Uihlein, D. C. Tsui, and A. C. Gossard, J. Vac. Sci. Technol. B **1**, 427 (1983), and Solid State Commun. **46**, 545 (1983).

[5]K. Muro, S. Mori, S. Narita, S. Hiyamizu, and K. Nambu, Surf. Sci. **142**, 394 (1984).

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

[7]G. L. J. A. Rikkin, H. W. Myron, P. Wyder, G. Wiemann, W. Schlapp, R. E. Horstman, and J. Wolter, J. Phys. C **18**, 1175 (1985).

[8]Yu. A. Bychkov, Phys. Status. Solidi (b) **132**, K57 (1985).

[9]A. Gold, Z. Phys. B **63**, 1 (1986).

[10]W. I. Wang, E. E. Méndez, T. S. Kuan, and L. Esaki, Appl. Phys. Lett. **47**, 826 (1985).

[11]Z. Schlesinger, S. J. Allen, J. C. M. Hwang, and H. Q. Lee, in *Proceedings of the 17th International Conference on the Physics of Semiconmductors, San Francisco, California, 1984,* edited by D. J. Chadi and W. A. Harrison (Springer, New York, 1985).

[12]R. Lassnig, W. Seidenbusch, E. Gornik, and G. Weimann, in Proceedings of the Eighteenth International Conference on Physics of Semiconductors, Stockholm, Sweden, 1986 (unpublished).

[13]S. Das Sarma and F. Stern, Phys. Rev. B **32**, 8442 (1985).

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

[15]S. Das Sarma, Solid State Commun. **36**, 357 (1980).

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

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

[18]Yu. A. Bychkov, S. V. Iordanskii, and G. M. Eliashberg, Pis'ma Zh. Eksp. Teor. Fiz. **33**, 147 (1981) [JETP Lett. **33**, 143 (1981)].

[19]A. H. MacDonald, H. C. A. Oji, and S. M. Girvin, Phys. Lett. **55**, 2208 (1985).

[20]Z. Schlesinger, W. I. Wang, and A. H. MacDonald, unpublished.

[21]S. M. Girvin, A. H. MacDonald, and P. M. Platzman, Phys. Rev. B **33**, 2481 (1986).

[22]A. H. MacDonald, L. K. Liu, S. M. Girvin, and P. M. Platzman, Phys. Rev. B **33**, 4014 (1986).

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