Evidence for a Collective Ground State in Si Inversion Layers in the Extreme Quantum Limit

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Infrared measurements of the cyclotron resonance in the two-dimensional electron gas reveal a remarkable line narrowing and shift if and only if the lowest Landau level is partially occupied. This behavior cannot be explained in terms of single-electron models, and strongly suggests a highly correlated or crystallized ground state, whose properties are compared with existing theories.

At low densities and low temperatures the behavior of an electron gas is dominated by electron-electron correlations, leading to crystallization into a Wigner lattice.[1,2] Current speculation is that strong magnetic fields enhance the formation of such a correlated ground state.[3-10] In the extreme quantum limit, where only the ground Landau level is occupied, the kinetic energy associated with the electron degeneracy is quenched and the electron-electron interactions must overcome only the thermal kinetic energy to produce a crystallized ground state.

In the following we report the results of cyclotron resonance (CR), experiments in the two-dimensional electron gas in Si inversion layers produced in a Si metal-oxide-semiconductor field-effect transistor (MOSFET). The width and position exhibit a remarkable quantum effect that strongly suggests a condensation of the electron gas into a highly correlated ground state, if not a lattice, when the first Landau level is only partially occupied.

There have been a number of dc transport measurements in Si MOSFET's that suggest singular behavior in the lowest Landau level. Kawaji and co-workers[11,12] have observed two activation energies in the dc conductivity, and suggest that this behavior is caused by a pinned Wigner solid. Tsui[13] has also reported anomalies in the magneto transport that are sensitive to the measuring electric field. The CR data of Kennedy *et al.*[14] previewed the behavior described below; they observed line narrowing and shifting in the quantum limit. In fact, we incorporate their data[14] in the phenomenology developed to describe the present results. Similar behavior is observed in dc transport and CR in GaAs/GaAlAs heterostructures in the quantum limit.[15]

The cyclotron resonance experiments which we report here were performed on the n-type inversion layer of a (100)-oriented Si MOSFET with a 3825-Å-thick wet oxide. The p-type substrate was doped at $N_A \sim 1.2\times10^{15}/\text{cm}^3$. The 4.2 °K inversion threshold was $V_T = 1.35$ V, and the flat-band voltage was estimated to be $V_{\text{FB}} = -0.7$ V. Fixed oxide charge was estimated as $Q_{ss} \sim +4\times10^{10}/\text{cm}^2$. The measured peak mobility was $\mu \sim 16000\ \text{cm}^2/\text{V}\cdot\text{s}$. The inversion-layer electron density was determined from the applied gate voltage V_G and the oxide capacitance per unit area C_{ox} by $n_s = [(V_g - V_T)/e]C_{\text{ox}}$. The uncertainty in n_s is related to a corresponding uncertainty in V_T and is $\sim 1\times10^{10}/\text{cm}^2$.

The far-infrared conductivity was determined by measuring the fractional change in transmission through the device when the inversion-layer electrons are introduced. The experimental apparatus has been described elsewhere.[16] Two points are, however, worth emphasizing. The experiment measures the absolute conductivity without unknown scaling factors. Also, unlike previously reported cyclotron resonance experiments,[14,17] we fix the magnetic field and observe the frequency dependence with a spectrometer. The latter point is crucial. It will become apparent that the CR line shape and position depend on magnetic field in such a way that fixed-laser-frequency, swept-field experiments at the quantum limit are at best difficult to interpret.

At low enough temperatures (< 4.2 K) and electron densities, such that the inversion-layer electrons populate only the lowest-energy quantum state, the cyclotron resonance becomes extremely sharp and lies higher in frequency than $\omega_0 \equiv eB/m^*c$. A comparison of the observed CR with that expected for a mass $m^* = 0.19m_e$ and a scattering rate determined from a Drude fit to the zero-field conductivity from 30–55 cm^{-1},[16] is shown in Fig. 1. The observed width is ~5 times narrower. There is also evidence of additional absorption at low frequency.

As the electron density is increased, and other spin, valley, and Landau levels are populated, the resonance broadens and shifts to lower fre-

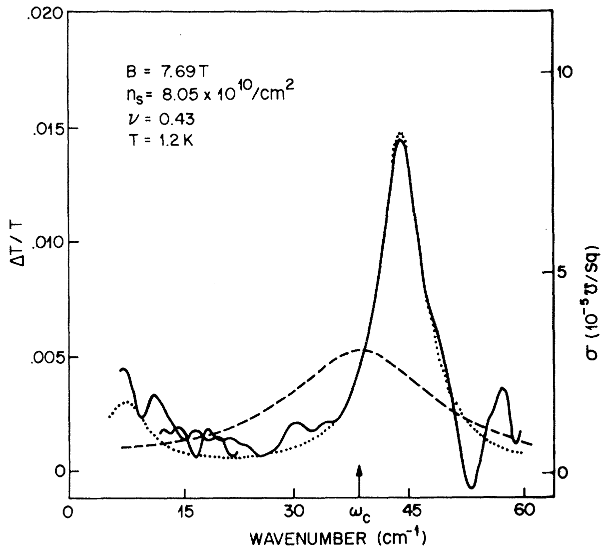

FIG. 1. Cyclotron resonance in the extreme quantum limit. The solid lines represent raw data; the structure is residual noise. The expected classical line shape is shown as a dashed line. The dotted line is a theoretical calculation of the frequency response of a pinned CDW with $m^* = 0.21m_e$ and a pinning frequency $\gamma = 20.2$ cm^{-1}, following Ref. 26.

quency. The variation in linewidth (full width at half maximum) and in the position of the resonance relative to ω_c are shown in Fig. 2 as a function of the filling factor, ν, which is defined as the ratio of the electron density to the degeneracy of the lowest valley, spin, and Landau level. Data are shown for magnetic fields ranging from 5 to 15 T, indicating that the critical parameter for this behavior is the filling factor ν rather than the electron density itself. Note that the figure includes data published by Kennedy *et al.*[14] It is apparent that the phenomenon described here was previewed by their experiments. Below $\nu \sim 0.5$, the characteristics of the resonance change very little, and it is the sharp resonance observed in this range which is discussed in the following.

The position of the resonance for $\nu \lesssim 0.5$ is plotted versus magnetic field in Fig. 3. The data appear linear in magnetic field, with a slope corresponding to a mass of $0.21m_e$—close to the band mass of $0.19m_e$. Thus it is more meaningful to characterize these data as exhibiting a shifted cyclotron resonance,[14] rather than a reduced effective mass. The magnitude of the shift is ~ 10 cm^{-1}.[18]

The behavior of the resonance was also stud-

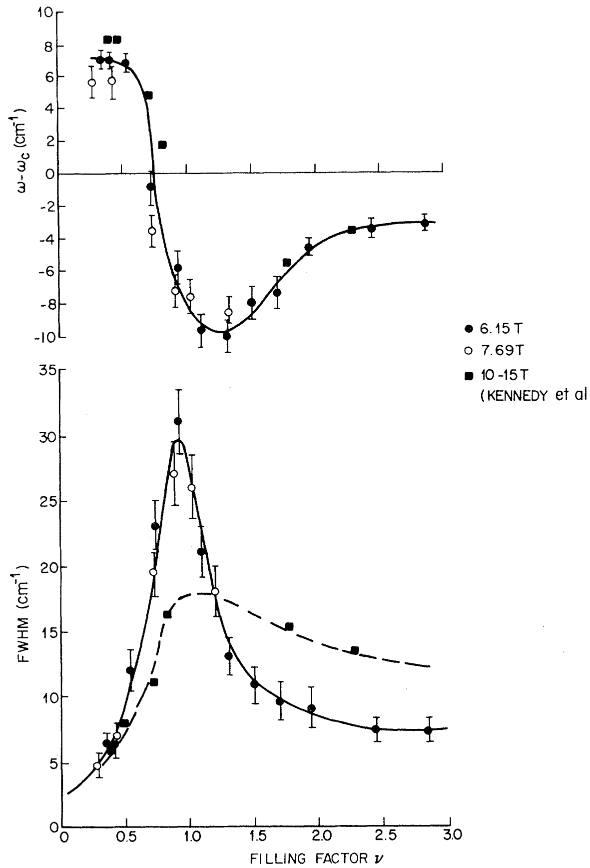

FIG. 2. CR position and width vs filling factor ν. Data published by Kennedy *et al.* (Ref. 14) are shown as squares, and the larger width at higher ν reflects the lower mobility of that sample.

ied as a function of the electric field at the interface by applying substrate bias. When the elec-

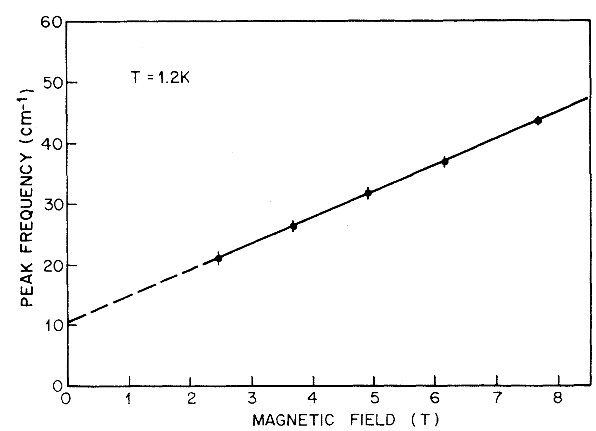

FIG. 3. Position of the CR peak vs magnetic field with n_s adjusted to maintain $\nu \lesssim 0.5$.

trons are pulled closer to the interface by a stronger electric field, the result is a larger shift and a broader, more asymmetric line. The shift appears to be proportional to the electric field to the one-third power, and thus inversely proportional to the wave-function thickness perpendicular to the interface.

As the temperature is raised, the resonance broadens and shifts to lower frequency. At the same time, a background peaked at $\sim\omega_c$ with a width comparable to the zero-field Drude width is seen to rise and eventually predominate. This occurs across the temperature range of 5–20 K. No apparent differences are seen in the temperature dependence observed at different values of electron density, electric field, or magnetic field.

By far the most dramatic effect observed is the extreme narrowing of the cyclotron resonance. In comparison to a typical Drude width due to random momentum scattering, the width below $\nu = 0.5$ can be narrower by more than a factor of 10. This strongly suggests the presence of a collective ground state in the lowest Landau level.

It is unlikely that the observed behavior is caused by conventional trapping,[19, 20] which would occur if the trap density were much less than the Landau-level degeneracy.[21] Under these conditions, however, the number of electrons contributing to the shifted cyclotron resonance would be fixed by the trap density, not the Landau-level degeneracy as shown in Fig. 2. This is also true for the model proposed by Ngai and White.[22] More interesting is the situation where the trap density or number of scattering centers exceeds the level degeneracy. Discrete trap levels do not occur. The Landau level is broadened by the dense-scattering centers and the breadth is expected to be comparable to or greater than the Drude scattering rate.[23] The strong line narrowing is not a feature of the one-electron theories of Ando[23] and Aoki.[24]

Although the basic idea of electron crystallization is a relatively old one,[1] the theoretical development of these ideas in the presence of a quantizing magnetic field (i.e., where only the lowest Landau level is occupied) are much more recent.[3-10] Current theory predicts that the ground state at zero temperature will be a Wigner-like solid with lattice spacing determined by the electron density and a critical temperature given by classical arguments.[7, 25] In particular, at $n_s = 10^{11}/\mathrm{cm}^2$, in strong magnetic fields one might expect a melting temperature $T_m \lesssim 0.6$ K. This is well below our lowest experimental temperatures.

On the other hand, Fukuyama, Platzman, and Anderson[7] suggest that at higher temperatures a charge-density-wave state (CDW) might exist, with a period of the cyclotron radius $l = (\hbar c/eB)^{1/2}$, and a critical temperature as large as $T_c \sim 0.5\nu(1-\nu)e^2/\epsilon l k_B$, where e is the electron charge, ϵ an appropriate dielectric constant, and k_B Boltzmann's constant. For $B \sim 10$ T, this corresponds to $T_c \sim 30$ K, nearly two orders of magnitude larger than the melting temperature of the classical Wigner crystal, and in the range of temperatures sampled in this experiment. More recent predictions by Yoshioka and Fukuyama,[10] where the CDW spacing was not selected *a priori*, also suggest a comparable critical temperature. Should such a CDW become distorted and pinned to the interface by random potential fluctuations at the surface, the result would be a sharp, shifted CR with an additional absorption peak at low frequency. In fact, a reasonable fit to the absorption line shape with a theoretical model of the pinned CDW developed by Fukuyama and Lee[26] can be made and is also shown in Fig. 1.

Other specific predictions of the current theories, however, are not supported by the observations. For example, Fukuyama, Platzman, and Anderson[7] predict a specific dependence of the CDW transition temperature on the magnetic field and the filling factor where none is observed. Likewise, the pinning frequency of the CDW in the model of Fukuyama and Lee[26] depends on parameters which are expected to vary with the electron density, contrary to experiment. It must be noted, however, that the magnetic field in these experiments is not sufficiently high to ensure negligible mixing of higher Landau levels by the electron-electron interactions, a condition assumed in these models.

In conclusion, we have observed a strong line narrowing and position shift of the cyclotron resonance keyed to an occupation of the lowest valley, spin, and Landau level. Although the shift must come from a coupling of the electron to the lattice,[27] be it impurity pinning or self-trapping by a lattice deformation, a strong line narrowing and shift depending critically on the filling factor ν appear to be outside the realm of one-electron theories. Consequently, this behavior strongly suggests that the ground state under these conditions becomes highly correlated, if not crystallized. This should encourage theorists who have predicted bizarre behavior in this limit. The existing theories, however, fail to give good account of some of the important details. In a longer manuscript we will discuss the experimental results in more detail, and make more quantitative comparisons with existing theory.

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Valence Changes in an Ytterbium-Aluminum Alloy during Autoionization and Auger-Electron Emission

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A valence change from f^{13} to f^{14} occurs in ytterbium atoms in a mixed-valent ytterbium-aluminum alloy during autoionization and Auger-electron emission. In both of these emission processes the $4f$-shell occupancy increases when the shell becomes more tightly bound under the influence of the core hole. The quenching of the core hole, which terminates the process, occurs after the valence change, so that the f^{13} initial state is not manifest in the spectra.

In this Letter we present the first evidence that ultraviolet photoelectron spectroscopy (UPS) and Auger-electron spectra can reflect a valence-electron configuration which has been changed from the initial-state configuration under the influence of a core hole. This effect is dramatic in the alloy we have studied, and may be typical of the lanthanide series of rare-earth elements. This issue is an important one since x-ray photoelectron spectroscopy (XPS) and UPS are increasingly being used to determine the initial-state configurations of the rare-earth elements both in