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Collective cyclotron resonance in a quasi-three-dimensional electron gas

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Far-infrared magnetotransmission measurements are carried out on modulation-doped wide parabolic $Al_xGa_{1-x}As$ quantum wells. We report the first observation of plasma-shifted cyclotron resonance in a semiconductor space-charge layer. The bulk carrier density deduced from the plasma frequency is found to be independent of the areal electron density. The homogeneity of the three-dimensional electron density is probed using this new resonant mode.

Recently a semiconductor heterostructure in which a conducting layer nearly free of impurities and sufficiently thick so that three-dimensional (3D) effects may occur was suggested.[1] Such structures are now being grown by molecular-beam epitaxy using a graded $Al_xGa_{1-x}As$ quantum well with modulation-doped $Al_yGa_{1-y}As$ barriers ($y > x$).[2-8] In these structures a nearly uniform density of electrons $n_0 \simeq 2\times 10^{16}$ cm^3 can be obtained over a width of about 1000 Å with the ionized donors removed several hundred angstroms from either side of the quantum well. In recent reports,[2-8] experimental results *suggest* the 3D character of the electrons in these structures without, however, providing a definite signature of three dimensionality. Firmly establishing their 3D behavior is a necessary first step toward the study of possible collective phases of these quasi-3D (Q3D) electron-gas systems at very low temperatures.[1,9] In this Rapid Communication we report the first observation of plasma-shifted cyclotron resonance in these structures and, therefore, in semiconductor space-charge layers. This observation provides direct evidence for 3D behavior of the carriers. The observed resonance is shown to be a powerful probe of the Q3D electron-gas system.

To obtain a Q3D electron gas we have grown quantum wells with an energy-band profile tailored to cancel the Hartree potential of the free-electron gas.[2-8] In our samples the Al composition x was varied quadratically from $x=0$ at the center to $x=0.15$ at the edges of a 1600-Å-wide $Al_xGa_{1-x}As$ layer leading to a parabolic-shaped potential well sandwiched between two barrier layers of composition $y=0.38$. This potential is exactly that needed to cancel the Poisson potential of a homogeneous 3D electron gas of density $n_0=2.5\times 10^{16}$ cm^3.[10] The finite width of the well leads to quantization of the electron energy levels. Magnetotransport experiments at very low temperatures have shown such a one-dimensional quantization when a magnetic field is applied perpendicular to the sample, as manifested by the integer[2,5,7,8] and fractional[10] quantum Hall effects. Analysis of the low-field Shubnikov–de Haas oscillations showed that between 1 and 3 electric subbands were occupied, depending on the areal electron density N_s.[10] To calculate the quantum states the Schrödinger equation must be solved self-consistently with the Poisson equation for the total potential. Model calculations show[4,7,8,10] that the total potential is approximately flat in the well center when $L=N_s/n_0 > a$, where $a=(\hbar/m^*\omega_0)^{1/2}$ is the width of the ground-state wave function of the bare potential, and ω_0 is the corresponding harmonic-oscillator frequency. When a magnetic field **B** is applied parallel to the sample plane the bulk limit is reached when the magnetic length l_0 ($l_0^2=\hbar/eB$) satisfies $l_0 \ll L$. This is specifically the configuration in which the electron gas is considered as Q3D.

In a thick metallic film, cyclotron resonance (CR) is usually detected in magnetotransmission with normally incident light of wave vector **q**. In this Faraday geometry ($\mathbf{q}\parallel\mathbf{B}$) one observes a resonant absorption of the electromagnetic radiation at the frequency $\omega_c=eB/m^*$, corresponding to the single-particle cyclotron excitation. In the Voigt configuration ($\mathbf{q}\perp\mathbf{B}$), the magnetic field lies in the plane of the electron slab and the carriers in their cyclotron motion are coupled to one another by the macroscopic depolarization field leading to a collective or plasma-shifted cyclotron resonance (PSCR).[11] The PSCR is excited by the electric component **E** of the incident electromagnetic radiation perpendicular to **B** at the frequency $\omega=(\omega_c^2+\omega_p^2)^{1/2}$, where ω_p is the plasma frequency of the uniform 3D electron gas. The PSCR is usually not observed in a quasi-2D electron system since cyclotron motion perpendicular to the confinement plane is not possible. Therefore a necessary condition for the PSCR is that l_0 is smaller than the effective quantum-well width. This condition can be achieved in inversion layers of narrow-gap semiconductors such as PbTe (Ref. 12) and InSb.[13] In this case, however, experiments carried out in the Voigt geometry[14] have shown that only the CR is observed with no characteristic plasma shift associated with the PSCR. The absence of the PSCR in those systems was attributed to the nonuniformity of the electron density across the quantum well.[14,15] The experiments reported here on Q3D heterostructures demonstrate convincing-

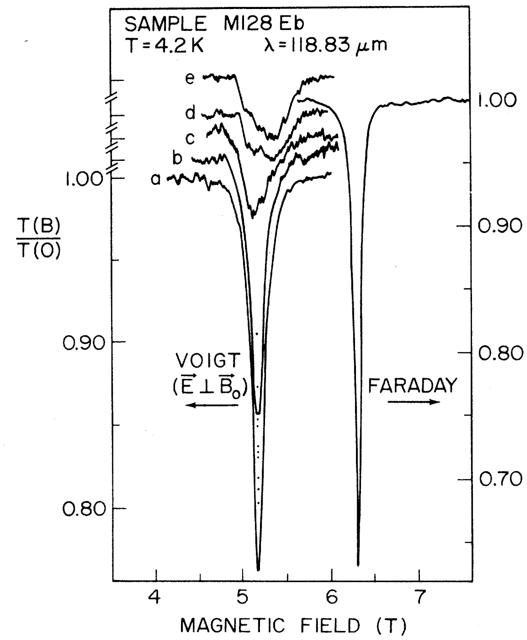

FIG. 1. Faraday CR (right) and Voigt PSCR (left) are measured at the same laser frequency. The Voigt resonance is shifted to lower field compared to the CR. The PSCR are measured under different filling conditions. The points are the position of the minima of transmission for different areal electron densities.

ly that both length and homogeneity criteria are achieved in a Q3D system.

The far-infrared magnetotransmission measurements were performed both by laser- and Fourier-transform spectroscopy allowing detailed analysis of the resonance line shape and its frequency dependence $\omega(B)$. In both Faraday and Voigt measurements, the far-infrared radiation was guided by a light pipe system through a linear polarizer placed a few millimeters before the sample. The transmitted light was detected by a composite Ge bolometer located outside the magnetic field. The sample substrate was wedged by 3° in order to avoid line-shape distortions due to interference fringes. The sample was cooled very slowly (over several hours) in the dark from room temperature down to 4.2 K. Since the areal density was found to be sensitive to visible light, a red light-emitting diode (LED) was mounted just in front of the sample, so that N_s could be varied. The experiments were carried out on four different samples grown independently and the results were found qualitatively reproducible. Here we show the results for our highest mobility sample.

A typical CR spectrum measured in the Faraday geometry is shown in Fig. 1. The magnetic-field dependence of the CR frequency is shown in Fig. 2. The low-field slope corresponds to an effective mass $m^* = 0.069m_0$. Deviation from linearity above 5 T is attributed to band nonparabolicity.[16] A line-shape analysis of the CR within the Drude approximation for the dark cooled sample gives $N_s = 1.8\times10^{11}$ cm^{-2} with a cyclotron scattering time $\tau = 20$ ps for $B = 6.30$ T. When the LED is activated, the peak intensity of the CR absorption reduces from 40% to 3%. When the LED is turned off, the absorption strength grows slowly and eventually (after ≅1h) becomes larger than the initial case corresponding to a maximum $N_s = 2.8\times10^{11}$ cm^{-2}. At the same time τ decreases to 9.5 ps. This behavior results from the change in the areal electron density by photoconductive and persistent-photoconductive effects, respectively.[17] By this means, the CR were measured with N_s between 4×10^9 and 2.8×10^{11} cm^{-2}. The decrease of τ in the region of

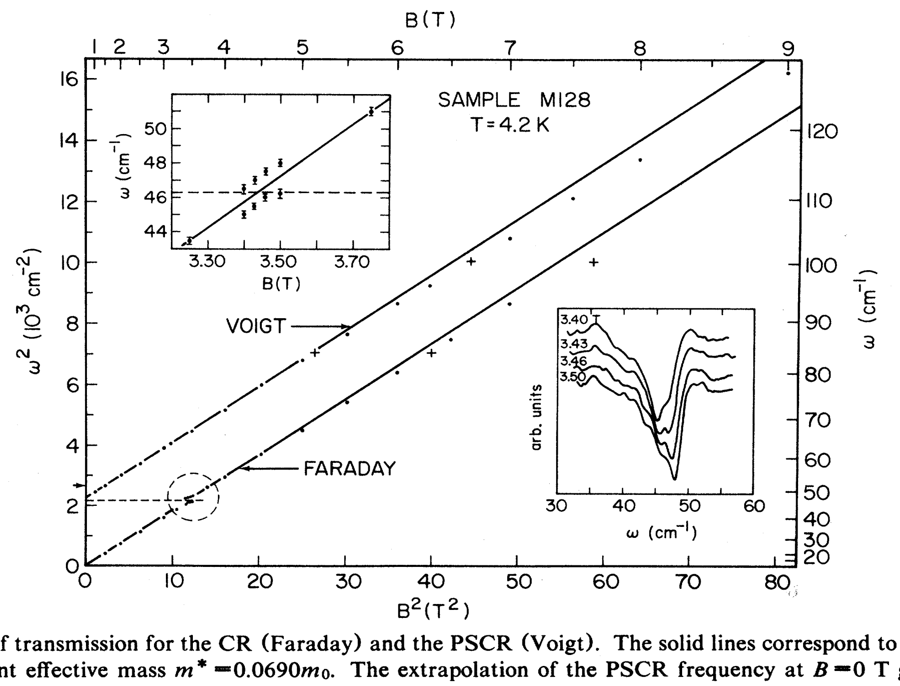

FIG. 2. Minimum of transmission for the CR (Faraday) and the PSCR (Voigt). The solid lines correspond to the predicted PSCR and CR with a constant effective mass $m^* = 0.0690m_0$. The extrapolation of the PSCR frequency at $B = 0$ T gives ω_p. The insets show CR spectra and energy dependence at the depolarization shifted intersubband frequency.

$N_s > 1\times10^{11}$ cm^{-2} is ascribed to the increased alloy disorder that the electrons experience as their wave function extends further into the higher Al concentration region of the graded layer. Detailed analysis of the dependence $\tau(N_s)$ is beyond the scope of this paper and will be presented elsewhere.

In the Voigt geometry, the measurements were performed under two conditions of light polarization. For $\mathbf{E}\parallel\mathbf{B}$ there is no resonance. When $\mathbf{E}\perp\mathbf{B}$, an absorption line is observed as shown in Fig. 1, which is shifted to lower fields (or higher frequencies) than expected for CR. The frequency dependence of the resonance $\omega(B)$, shown in Fig. 2, obeys a quadratic relation $\omega^2=\omega_c^2+\Omega^2$. The polarization selection rules and the frequency dispersion of this resonance provide clear evidence that we are observing a bulklike PSCR (or collective cyclotron resonance). The intercept Ω^2 is then given by ω_p^2 and is measured from the $B=0$ extrapolation as $\omega_p=47.5\pm0.5$ cm^{-1}. Relating the 3D electron density n_0 to ω_p by $\omega_p^2=n_0e^2/m^*\epsilon_0\epsilon$ we find $n_0=2.25\times10^{16}$ cm^{-3} using a static dielectric constant $\epsilon=13$ for GaAs. Our determination of ω_p from the zero-field extrapolation can be corrected for the coupling of the PSCR to the macroscopic polarization field carried by the longitudinal-optical phonon.[18] Taking $\Omega^2=47.5$ cm^{-1}, we calculate[18] $\omega_p=51.5$ cm^{-1} (indicated by the arrow in Fig. 2). This leads to a corrected 3D electron density $n_0=2.65\times10^{16}$ cm^{-3}. Although this value seems to be in better agreement with the design density,[8,10] uncertainty in the true curvature of the well precludes a definitive comparison.

The PSCR spectra taken for different values of N_s are shown in Fig. 1. Remarkably, the resonance position of the PSCR is nearly independent of N_s. This result shows that ω_p, and hence n_0, are independent of the electron areal density. This effect demonstrates experimentally that the electron gas spreads uniformly across the well until the appropriate region of the fictitious positive uniform background (here simulated by the parabolic built-in potential) is neutralized. The effective thickness of the electron plasma is then proportional to N_s. This remarkable effect indicates that, to create a uniform 3D electron plasma, precise control of the donor doping in the barrier is not necessary, instead only good control of the quadratic Al profile is required.

To determine N_s from the PSCR approximation line we have modeled the line shapes, within the Drude approximation, for the case of the Voigt geometry. The relative transmittance amplitude of the Q3D heterostructure is then given by the 2D expression

$$t=\left[1+\frac{\sigma_e(\omega)/Y_0}{1+\sqrt{\epsilon}}\right]^{-1},$$

where Y_0 is the wave transmittance, $Y_0=(377\,\Omega)^{-1}$, and $\sigma_e(\omega)$ is the effective 2D Drude conductivity given by

$$\sigma_e(\omega)=i\frac{N_s'e^2}{m^*}\frac{\omega_p^2-\omega(\omega+i/\tau)}{\omega_p^2(\omega+i/\tau)-\omega(\omega+i/\tau)^2+\omega\omega_c^2}.$$

Here the density N_s' is the areal density of the 3D-like electrons contributing to the PSCR. Under different LED illumination conditions N_s' could be increased up to 1.8×10^{11} cm^{-2}, corresponding to the effective thickness, $L'=N_s'/n_0$, of the 3D-like slab, varying up to 80 nm. At maximum filling, the areal carrier density ($N_s'=1.8\times10^{11}$ cm^{-2} measured at 5.17 T) is significantly smaller than N_s measured in the Faraday case (2.8×10^{11} cm^{-2}). We attribute this apparent discrepancy to the states near the edges of the electron slab in the Voigt experiment where the electron density is inhomogeneous so that they do not contribute to the PSCR.[14,15] The values of τ determined from the transmittance model ranged from $\tau=3$ to 6 ps as N_s' varied between the above-mentioned values. The discrepancies in the *apparent* scattering time compared with the Faraday CR measurements may be a consequence of fluctuations in the 3D densities leading to an artificial broadening of the PSCR. In the Faraday case, on the other hand, the quantum confinement along the growth direction quantizes the observable values of m^* and τ in the resonance. This raises the important question of the limit of the grading control that can be reached in the growth of these Q3D systems in order to obtain a homogeneous 3D electron density. PSCR line-shape analysis can be a powerful tool for the characterization of the density homogeneity of the electron gas.

In the case of very low filling conditions, the electrons are confined in the parabolic built-in potential which gives rise to a harmonic-oscillator spectrum with frequency $\omega_0=(n_0e^2/\epsilon_0\epsilon m^*)^{1/2}$. This harmonic spectrum is valid for electron areal density $N_s\ll n_0a$. In the Voigt geometry experiment, an intersubband resonance should then be observed at the frequency $\omega_0^2+\omega_c^2$ which would be identical to the PSCR frequency. In our measurements, the low filling limit was approached but not rigorously achieved. As N_s decreases, the PSCR becomes first asymmetric toward the high-field region [Fig. 1(c)], splits into a two resonances [Fig. 2(d)], and then becomes displaced to slightly higher field [Fig. 1(e)]. This indicates the existence of an unresolved resonance located in the low-field side of the PSCR whose origin is not yet completely understood. Such a behavior is not observed in Faraday geometry spectra. Further study will be required to elucidate the complex low-density spectra.

We now discuss a connection between the 2D and the 3D case. As shown in the insets of Fig. 2, the CR of the two 2D electron gas splits into two resonances centered on $B=3.43$ T. As the field is changed from 3.40 to 3.50 T, the oscillator strength is gradually transferred from the lower-frequency peak to one at the higher frequency. This splitting was reported earlier[4] and interpreted in terms of mode coupling between the CR and the intersubband resonance. This coupling is allowed by the small misalignment angle (3°) between B and the growth axis.[19] As shown previously,[4] this mode mixing is resonant at the value of the depolarization[20] shifted optical intersubband resonance frequency which was found to be remarkably close to the calculated 3D plasma frequency deduced from the growth parameters (i.e., the curvature of the parabolic well). Here we demonstrate experimentally (to within our experimental accuracy of ±0.5 cm^{-1} for ω_p) that these two frequencies are indistinguishable. This is best seen in Fig. 2 by the dashed line connecting the CR splitting and the plasma frequency ω_p. Recently this result was demonstrated[21] to be a consequence of the generalization of the Kohn theorem[22] to the case of parabolic quantum wells: The depolarization shifted intersubband resonance occurs at the normal mode frequency of the *empty* parabolic well ω_0, which by construction is equal to ω_p.

In conclusion, by observing the PSCR we have demonstrated 3D plasma behavior in a wide parabolic well when the magnetic field is applied along the electron slab. The PSCR mode is shown to be a powerful investigative tool for such new structures since it allows independent measurement of the 3D plasma frequency and the areal electron densities. Moreover, information is obtained on the homogeneity of the 3D electron gas.

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