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LIGHT SCATTERING FROM ELECTRON PLASMAS IN A MAGNETIC FIELD

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We have observed Raman scattering from the hybrid plasma mode in n-GaAs and its coupling with the Bernstein modes at harmonics of the cyclotron frequency.

We report Raman scattering of 1.06-μ radiation by two coupled elementary excitations of the electron gas in GaAs, the hybrid plasma mode and the collective Bernstein modes at $n\omega_c$ with $n \geq 2$ (where $\omega_c = eB/m^*c$ is the cyclotron frequency). Raman scattering by various modes of electron gas in semiconductors, including pure plasmons,[1,2] pure collective Bernstein modes,[2-4] single-particle excitations of the Landau levels of the electron gas,[2,3] and the coupled optic-phonon-plasmon modes,[1,5] has been recently reported. In the present experiments the application of a magnetic field to an electron gas gives rise to observable Raman scattering from the hybrid plasma mode[6] which involves the coupling between the plasmons and ω_c, the cyclotron-frequency excitations. In addition, scattering in the region of $\omega_p = (n^2-1)^{1/2}\omega_c$, where $\omega_p = (4\pi ne^2/m^*\epsilon_0)^{1/2}$ is the plasma frequency of the electron gas, is expected[7] to give information about the coupling between the Bernstein modes[8] and the hybrid mode. The frequency shifts and the line broadening of the scattered light in our experiments show the effect of such coupling.

The scattering experiments were carried out at 1.06 μ using a 3- to 10-W Nd-doped yttrium-aluminum-garnet laser. GaAs with electron concentrations from 1.6×10^{16} cm^{-3} to 1.4×10^{17} cm^{-3} were investigated. The laser was incident along a $\langle 100 \rangle$ axis and the scattered radiation was collected along a $\langle 010 \rangle$ axis. A superconducting solenoid provided magnetic fields up to 100 kOe. Two scattering geometries were investigated: $\vec{k} \perp \vec{B}$ (Fig. 1) and $\vec{k}$ at 45° to $\vec{B}$ (Fig. 2), where $\vec{k} = \vec{k}_i - \vec{k}_s$ is the wave vector of the excitation causing the scattering and $\vec{k}_{i,s}$ are the wave vectors of the incident and the scattered radiation, respectively. The experiments were carried out at a sample temperature of 300°K where the electron gas is nondegenerate. The scattered light was analyzed with a tandem spectrometer and detected with a cooled S-1 phototube.

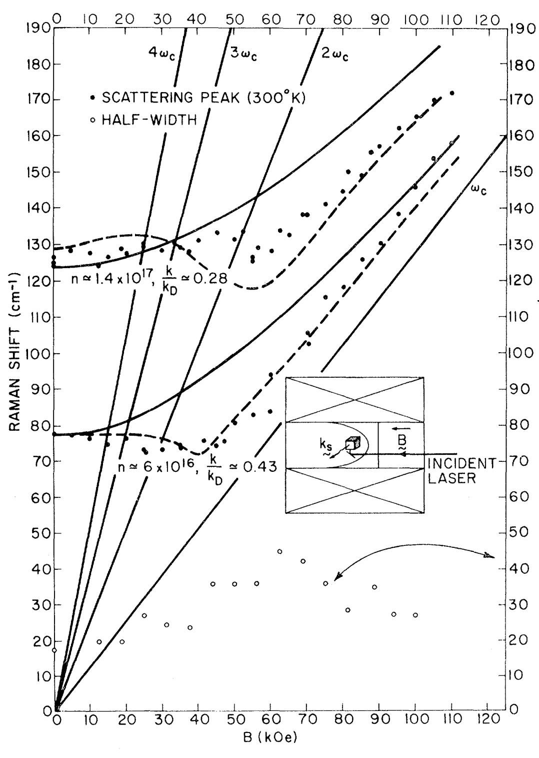

FIG. 1. Frequency shift as a function of $\vec{B}$ of inelastically scattered light with $\vec{k} \perp \vec{B}$ from coupled plasmon-cyclotron modes of electron gas in n-GaAs for three different electron densities, and half-width of the above scattered light for $n_e \approx 1.6\times10^{17}$ n-GaAs sample.

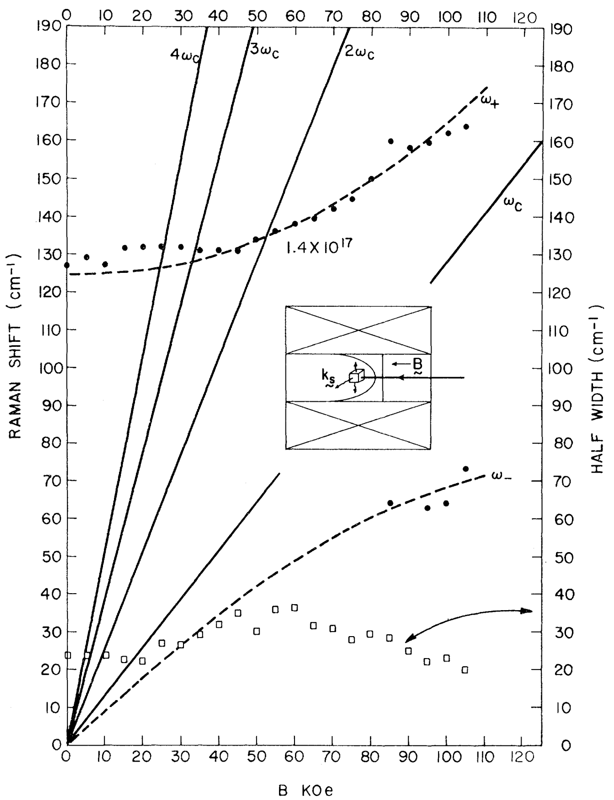

FIG. 2. Frequency shift as a function of B of inelastically scattered light with $\vec{k}$ at 45° to $\vec{B}$ from coupled plasmon-cyclotron modes of electron gas in n-GaAs.

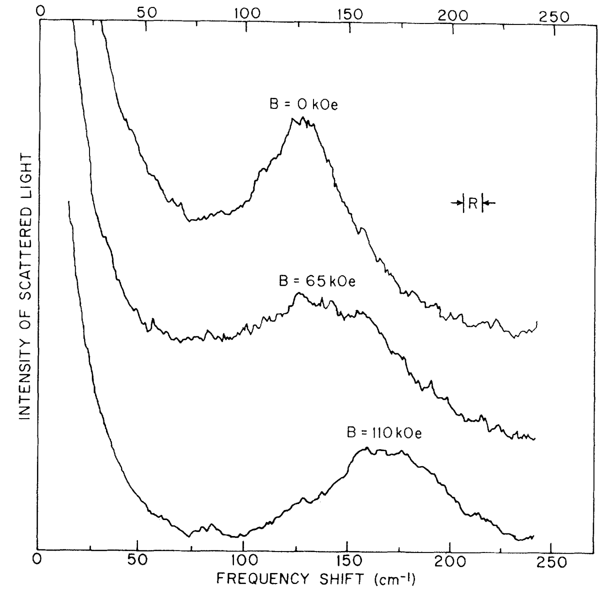

FIG. 3. Typical Raman spectrum of GaAs ($n_e \approx 1.4 \times 10^{17}$ cm^{-3}) at 300°K at three values of B for $\vec{k} \perp \vec{B}$. Notice that the plasmon-scattered line is narrow and well resolved in (a) and (c) but in (b), when $\omega_p \approx \sqrt{3}\omega_c$, the linewidth increases by nearly a factor of 2.

GaAs samples had a dc mobility of 4000-4500 cm^2 V^{-1} sec^{-1} which gives an electron collision time $\tau \approx 1.6\text{-}2.0 \times 10^{-13}$ sec and an expected plasmon half-linewidth of ~20 cm^{-1} (in absence of Landau damping which will affect the linewidths in the low-carrier-concentration samples[5] in zero magnetic field).

Figures 1 and 2 show the frequency shift of the plasmon scattered light as a function of B for the geometries $\vec{k} \perp \vec{B}$, and $\vec{k}$ at 45° to $\vec{B}$, respectively. The case where $\vec{k} \perp \vec{B}$ is more interesting of the two and hence was studied in greater detail, and we present results for samples with two different carrier concentrations in Fig. 1, where we also show the calculated position of the hybrid mode given by $\omega = (\omega_p^2 + \omega_c^2)^{1/2}$ in the limit where $(k/k_D)^2 \ll 1$, where k_D is the Debye wave vector. It is seen that the experimental data agree with the simple curve only at very low magnetic field and at the highest magnetic fields. For the intermediate B there is a pronounced departure of experimental points from the hybrid plasmon. In Fig. 2, the discrepancy between the measured frequency shift and the resonance positions calculated using the long-wavelength formula for $\vec{k}$ at 45° to $\vec{B}$, $\omega_\pm = \{\frac{1}{2}[\omega_p^2 + \omega_c^2 \pm (\omega_p^4 + \omega_c^4)^{1/2}]\}^{1/2}$, is seen to be small. It is interesting to note here that Raman scattering from the lower hybrid plasma mode is a unique probe of its frequency and linewidth since the plasma is opaque in this region below the upper hybrid for direct absorption measurements.

In addition, from the lower part of Fig. 1 it is seen that the linewidth of the collective-mode-scattered light for the case of the 1.4×10^{17}-cm^{-3} GaAs sample nearly doubles from a value of ~20 cm^{-1} at $B = 0$ to about 45 cm^{-1} at $B = 65$ kOe where $\omega_p = \sqrt{3}\omega_c$, and a crossover is expected to occur between the hybrid plasmon and the $2\omega_c$ Bernstein mode. Notice that the discrepancy between the simple hybrid calculated curve for the frequency shift and the measured frequency shift for this sample is also the largest at this field. For higher B the linewidth again shrinks and returns to a value somewhat larger than that at $B = 0$.

Figure 3 shows typical traces of scattered light as a function of the frequency shift for $B = 0$, 65, and 110 kOe for the 1.4×10^{17}-cm^{-3} GaAs sample. The plasma line is narrow and well defined at zero as well at the highest magnetic field, but at $B = 65$ kOe there is the anomalous broadening mentioned above. The measured integrated intensity of the plasmon-scattered line decreased by ~25% as B is changed from 0 to 110 kOe in qualitative agreement with predictions.[7] Polarization studies showed that the scattered light was polarized parallel to the incident laser light indicating that the scattering occurs because of the density fluctuations of the electron gas. Coupling to the LO phonon can be neglected in the present experiments since even in the 1.4×10^{17}-cm^{-3} sample at $B = 110$ kOe the LO phonon was shifted by only 2 cm^{-1} from its zero-field value.

These frequency-shift discrepancies and the line broadening can be understood when we take into account the coupling between the hybrid mode and the Bernstein modes, which becomes large as k/k_D approaches 1. Strong coupling occurs when $\omega_p = (n^2-1)^{1/2}\omega_c$ where the Bernstein modes and the hybrid mode repel each other with a frequency splitting of the order of $(k/k_D)^{n-1}\omega_c$. This splitting for $n = 2$ is given by

$$\Delta\omega = \tfrac{3}{2}\sqrt{3}(k/k_D)\omega_c = 1.5kV_{th}, \qquad (1)$$

where the V_{th} is the thermal velocity of the electrons. The splitting for the two GaAs samples shown in Fig. 1 is about 50 cm^{-1} and is nearly independent of carrier concentration for $k/k_D \lesssim 1$. In the case where plasmon linewidth is determined by the electron collision time, it is easy to see that the split line can be resolved if $1.5kV_{th}\tau > 1$. For the samples studied here the plasmon half-linewidth is about 20-25 cm^{-1}, and thus the two components of the split line at $\omega_p = \sqrt{3}\omega_c$ cannot be resolved. However, the increase in the half-linewidth from 20 cm^{-1} at $B = 0$ to 45 cm^{-1} at 65 kOe (near the cross-over region) is in very good agreement with Eq. (1), which indicates a strong coupling between the Bernstein mode at $2\omega_c$ and the hybrid mode.

The scattering cross section for the various Bernstein modes is given by[7] $\sigma_n \simeq \sigma_1(k/k_D)^{2(n-1)}$, where σ_1 is the cross section for the hybrid mode. Thus in the low-concentration samples, where $k/k_D \sim 0.5$, we would expect to see sizable scattering at a number of Bernstein modes. When the plasmon linewidth is too broad to resolve the individual scattering peaks, as is the case here, we must use a weighted average of scattering from all the modes to determine the position of the peak. Results of such computer calculation by Foo and Tzoar[9] are shown by dashed lines in Fig. 1. A qualitative agreement is seen to exist between experiment and theory.

In conclusion all of our results indicate that in the range of k/k_D investigated here interesting coupling between hybrid plasma mode and the Bernstein modes can be studied by scattering from density fluctuations. It is clear that longer electron collision times available in epitaxial GaAs should allow the investigation of the effects of dispersion, damping mechanisms, quantum-limit effects, and degenerate plasmas ($T < 77°$K). At low temperatures where the plasma becomes degenerate, k_{FT} should replace k_D and the coupling effects should become temperature independent. Other semiconductor and lasers may be of interest; however, in our previous experiments with InSb and InAs using a CO_2 laser, $kV_F\tau$ was much less than that in the present experiment, and the coupling effects could not be observed.

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