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Dimensional resonance of the two-dimensional electron gas in selectively doped GaAs/AlGaAs heterostructures

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The polarization of small, disc-shaped regions of two-dimensional electron gas exhibit a well-defined collective resonance. The resonance and its behavior in a magnetic field are accurately described by two-dimensional electrons in a harmonic potential.

The dielectric response of composite materials comprised of small metal or dielectric particles dispersed in another dielectric exhibits resonances at frequencies given by the Maxwell-Garnett theory.[1] Formulated at the turn of the century to understand the "Colours of Metal Glasses," it continues to be the starting point for any discussion of the optical properties of inhomogeneous or composite material.[2-5] In the following we describe experiments on a two-dimensional (2D) analog of a composite system and report on the collective resonance of small 2D particles or devices. The resonance and its Zeeman effect are accurately given by the 2D limit of Maxwell-Garnett theory.

The samples used in this experiment were fabricated from a selectively doped molecular-beam epitaxial heterostructure.[6-9] A section is shown in Fig. 1. It consists of a heavily doped GaAs layer on top of a heavily doped $Al_{0.3}Ga_{0.7}As$ layer which is in turn grown on top of a 1-μm-thick nominally pure GaAs buffer layer. After removing the topmost GaAs layer, magnetotransport experiments at 4.2 K indicate that the (Al,Ga)As is depleted and a 2D electron gas with electron density, $n_s = 5.5\times10^{11}/\mathrm{cm}^2$, and mobility of 250 000 $\mathrm{cm}^2/\mathrm{V\,sec}$ exists at the interface between the (Al,Ga)As and GaAs buffer.

The 2D square array of disclike mesas, Fig. 2(a), was produced by defining the mesa with photoresist and then chemically etching the remaining GaAs and $Al_{0.3}Ga_{0.7}As$ with a 10/1 mixture of citric acid and hydrogen peroxide to a depth of ~1500 Å. The GaAs cap layer was subsequently removed by selectively etching the GaAs with hydrogen peroxide and ammonia. Figure 2(b) shows a cross section through the mesa with the $Al_{0.3}Ga_{0.7}As$ layer undercut by the final GaAs etch. The period of the array, b, is 4 μm while the diameter of the mesa or disc is approximately 3 μm.

The submillimeter wave response of this 2D array of discs was determined by measuring the absorptance of radiation transmitted normal to the surface. Typical data are shown in Fig. 3 where the effective sheet conductance is plotted versus frequency. With application of a magnetic field the

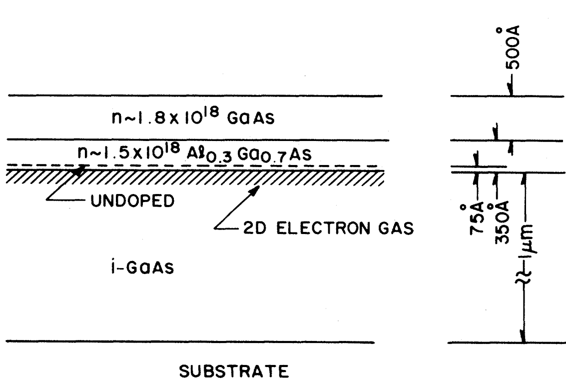

FIG. 1. Cross section through starting wafer grown by molecular-beam epitaxy.

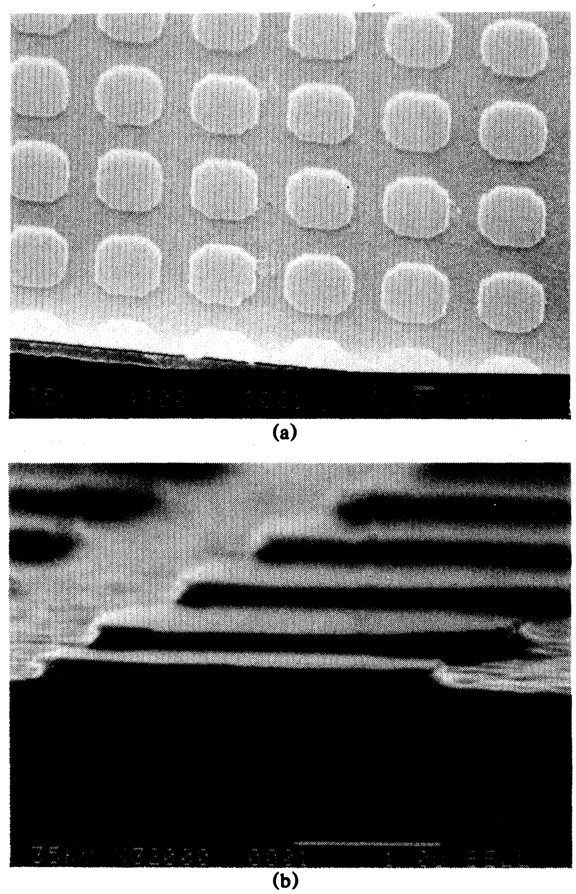

FIG. 2. (a) Two-dimensional array of disc-shaped mesas containing the two-dimensional electron gas. The period of the array, $b=4$ μm. (b) Cross section through the mesa. The $Al_{0.3}Ga_{0.7}As$ layer is visible as a ledge on the mesa.

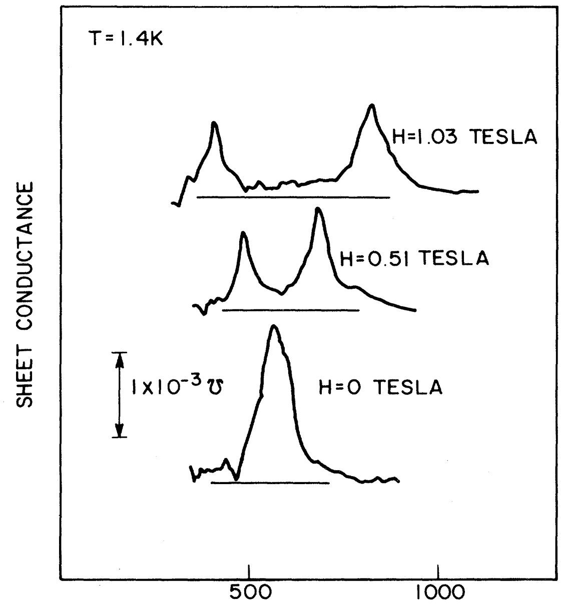

FIG. 3. Sheet conductance of array as a function of frequency. Magnetic field normal to the surface is a parameter.

resonance splits in two. As the magnetic field is raised, one mode approaches the cyclotron resonance, and the low-frequency mode tends toward zero but at an ever decreasing rate (Fig. 4).

To model the response of this system, we consider the disc of 2D electrons to be an oblate spheroid with small thickness, t. The internal field, E^-, is related to the external field, E^0, oriented in the plane of the disc, by

$$E^- = E^0 - LP \quad . \tag{1}$$

L is the depolarization factor for the thin oblate spheroid[9] and P the internal polarization:

$$LP = \frac{\pi}{4a\epsilon i\omega}(t\sigma_v)E^- \quad . \tag{2}$$

Here σ_v is an effective 3D conductivity, ϵ the dielectric constant in which the disc is imbedded, and a is the disc radius.

In the limit as $t \rightarrow 0$, $t\sigma_v$ approaches the 2D surface conductivity, σ_s, with appropriate units of mho/square ($1\text{mho} = 1\Omega^{-1}$). Further, we note that in the system shown in Fig. 2, the fringing fields that contribute to the depolarization field in the 2D limit are divided between free space and GaAs and we replace ϵ in (2) by $(\epsilon_0+\epsilon_1)/2$ where ϵ_0 and ϵ_1 are dielectric constants of free space and GaAs, respectively.

Then we have

$$E^- = \frac{E^0}{1+\pi\sigma_s/2a\,(\epsilon_0+\epsilon_1)i\omega} \tag{3}$$

and the average sheet conductivity

$$\sigma = f\frac{\sigma_s}{1+\pi\sigma_s/2a\,(\epsilon_0+\epsilon_1)i\omega} \quad , \tag{4}$$

where f is the fraction of the area covered by discs.

Assuming a classical Drude relaxation of the conductivity of the 2D electron gas

$$\sigma_s = \frac{n_s e^2 \tau}{m}\frac{1}{1+i\omega\tau} \quad , \tag{5}$$

we obtain the σ

$$\mathrm{Re}(\sigma) = f\frac{n_s e^2\tau}{m}\frac{1}{1+\omega^2\tau^2(1-\omega_0^2/\omega^2)} \quad . \tag{6}$$

n_s, e, τ, and m are the 2D electron density, charge, scattering time, and mass, respectively.

ω_0 is the resonance frequency for the disc given by

$$\omega_0^2 = \frac{n_s e^2 \pi}{am^* 2(\epsilon_0+\epsilon_1)} \quad . \tag{7}$$

In deriving (6) we have ignored interaction between discs.

Using the electron density for the starting material $n_s = 5.5\times10^{11}/\text{cm}^2$ gives $\omega_0/2\pi \cong 690$ GHz whereas the resonance occurs at 575 GHz. The scattering rate in the starting material is $1/2\pi\tau \sim 16$ GHz compared with a rate deduced from the linewidth in Fig. 3 at $H=0$ of 50 GHz.

To account for the discrepancy in measured ω_0 we must reduce the electron density of the disc by approximately 30%. We substantiate this interpretation by measuring the effective density in the surface from the integrated strength of the $H=0$ line.

$$\int_0^\infty \mathrm{Re}(\sigma)\,d\omega = \left(\frac{\pi a^2}{b^2}\right)\left(\frac{\pi}{2}\frac{n_s e^2}{m}\right) \quad . \tag{8}$$

The factor $\pi a^2/b^2$ is the filling factor, f, shown in (6). From (8) and the line strength shown in Fig. 3 we deduce a disc density of 3.7×10^{11} which is $\sim 33\%$ lower than that found in the starting material.

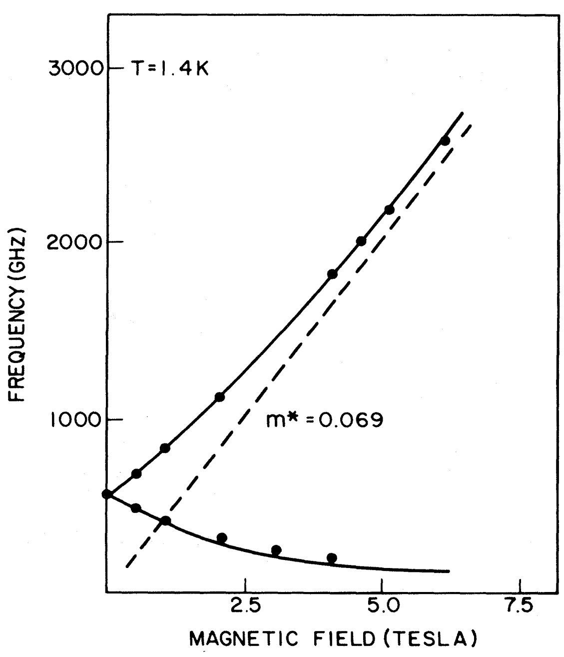

FIG. 4. Effect of magnetic field normal to the surface on resonance. Solid line is the theory in Eq. (4) in text. Dashed line is the cyclotron frequency eH/m^* with $m^* = 0.069$.

The increased scattering rate in the disc may be due to the processing (n_s is substantially reduced). But it is interesting to note that the electrons at the Fermi level collide with the edges of the disc at a rate which is comparable to the scattering rate in the starting material and may contribute to the broadening.

We also note that, whereas illumination of the starting material at helium temperatures increased the density by 32% and the mobility by 20%, similar illumination produced no perceptible change in line strength or resonant frequency. We conclude that after processing we were unable to alter the electron density in the disc by illumination. We have no explanation for this.

In a magnetic field, theory predicts two resonances,

$$\omega_{\pm} - \pm\omega_c/2 + [(\omega_c/2)^2 + \omega_0^2]^{1/2} \ , \tag{9}$$

where $\omega_c = eH/m^*$ is the cyclotron frequency. The solid line in Fig. 4 is derived from (4) with an effective mass $m^* = 0.069$ and leaves little room for improvement.

In conclusion, we have observed a resonance in the collective polarization of a disc of 2D electrons and find that the resonance position and magnetic field dependence are accurately given by the Maxwell-Garnett theory. The effective radius of the 2D electron gas agrees with the disc dimension to within experimental error (± 1000 Å) but the electron density in the disc has been reduced by approximately 30% compared to the starting material.

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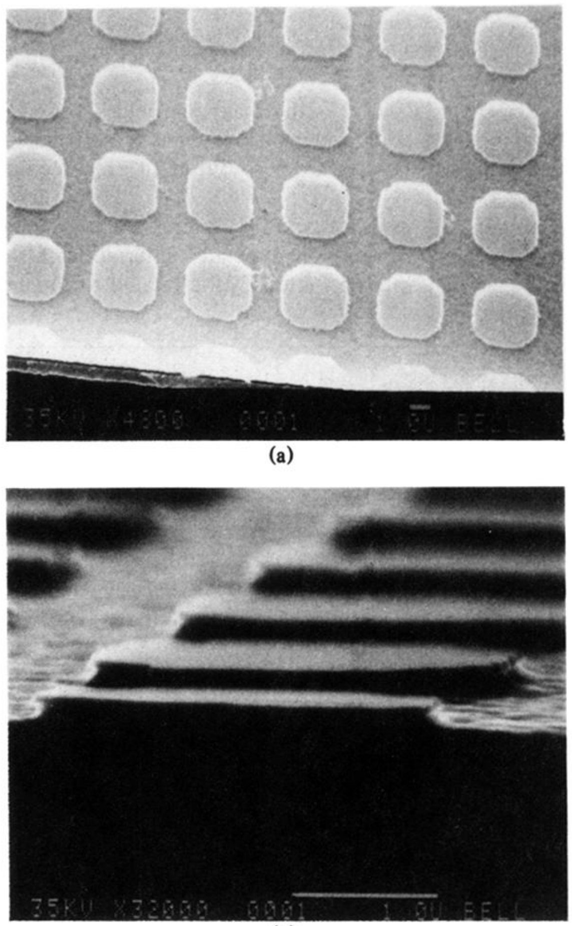

(a)

(b)

FIG. 2. (a) Two-dimensional array of disc-shaped mesas containing the two-dimensional electron gas. The period of the array, $b = 4\ \mu$m. (b) Cross section through the mesa. The $Al_{0.3}Ga_{0.7}As$ layer is visible as a ledge on the mesa.