Microwave Dimensional Resonances in Large Electron-Hole Drops in Germanium*

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In optically excited Ge at $T = 1.5$ to 4 K, we observe a series of new microwave resonances at 3 to 20 kOe for $\nu = 25$ GHz. The resonant fields increase markedly with light intensity and are strongly correlated with the 709-meV electron-hole drop luminescence. We interpret the new lines as magnetoplasma dimensional resonances of single drops of ~ 1 mm diam. We use magnetoplasma dimensional resonance as a direct probe of drop size and kinetics.

At high densities and low temperatures, excitons in Ge condense into electron-hole droplets (EHD).[1] Within a droplet the electrons and holes behave as a plasma of constant density $n_0 = 2 \times 10^{17}/\mathrm{cm}^3$. At such high densities, ordinary cyclotron resonance (CR) is magnetoplasma shifted.[2] In this Letter we show that a different microwave absorption associated with the drop dimensions is expected, and we report the observation of this phenomenon.

In addition to the usual bulk CR of optically excited free electrons and holes in Ge, we observe a series of new microwave resonances whose resonant fields depend markedly on light intensity.[3] We interpret these new lines as magnetoplasma dimensional resonances (MDR) of an EHD whose size increases with light intensity. We confirm this interpretation by simultaneously measuring the intensity I_{709} of the 709-meV luminescence of the EHD. The results are in good qualitative agreement with a simple theoretical model. MDR is a new tool for studying the size, shape, and kinetics of EHD.

A disk of polished and etched ultrapure p-Ge ($N_A = 10^{10}$ cm^{-3}) is mounted on a rotator in a tunable cylindrical cavity (Fig. 1) immersed in liquid He^4 in an optical cryostat. Both CR and MDR are observed with a high-sensitivity superheterodyne spectrometer. The beam of a variable-intensity cw Ar-Kr ion laser is mechanically chopped at 258 Hz and focused via lens F onto the crystal (100) face. The external magnetic field is accurately aligned such that $\vec{H} \parallel (001)$. The 709-meV luminescence was simultaneously detected using the optical arrangement of Fig. 1. We have observed CR, MDR, and I_{709} over the frequency range $24 \leq \nu \leq 26$ GHz for many Ge samples of diameter 3.9 mm and thickness l ranging from 0.89 to 1.65 mm. The usual cylindrical cavity modes were considerably shifted by the presence of the Ge sample. Although the relative intensities varied, the observed MDR were essentially

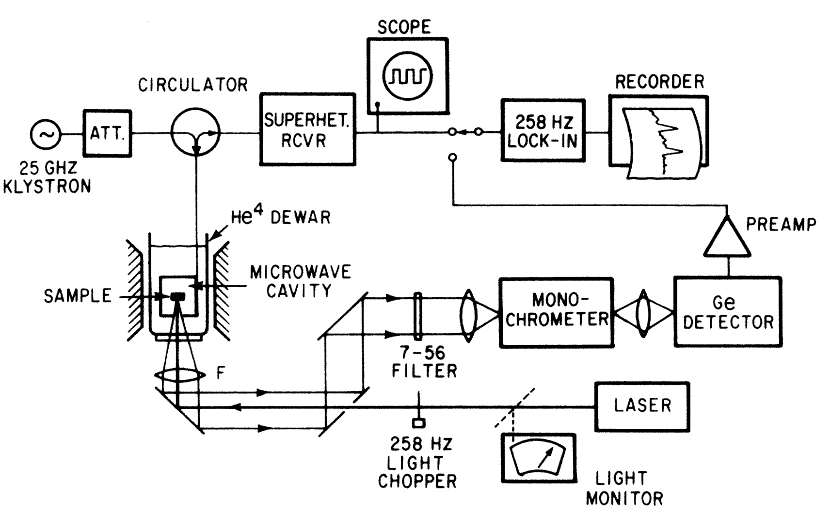

FIG. 1. Experimental arrangement for observing microwave absorptions of electron-hole droplets in optically excited Ge.

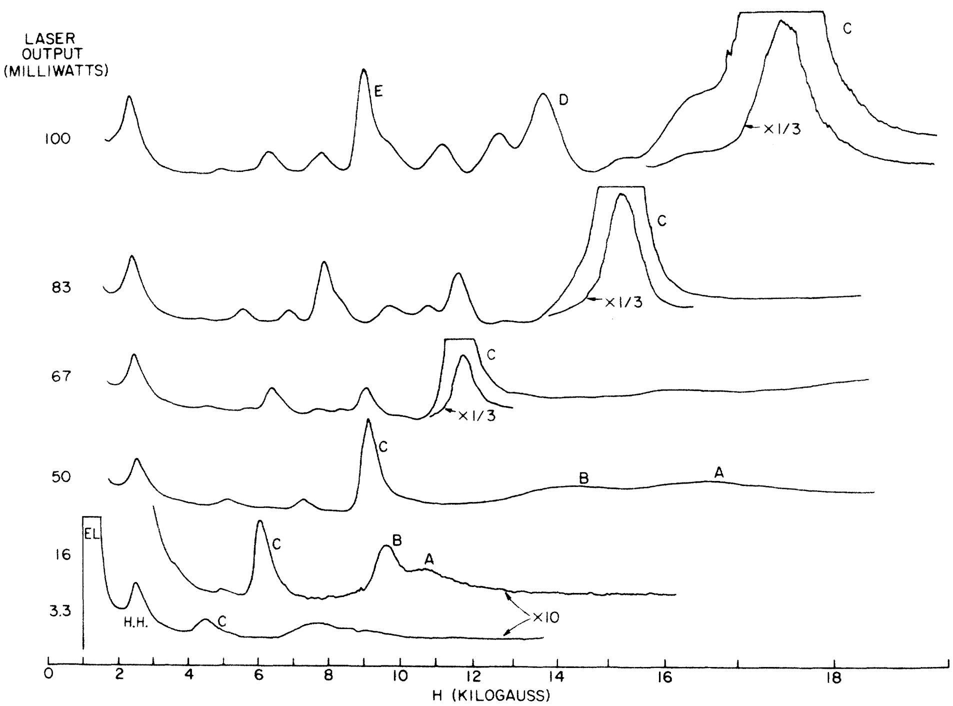

FIG. 2. Microwave absorption versus H in pure Ge (sample CR-1) at 1.6 K, $\nu = 25.22$ GHz, for various focused laser output powers P. The power absorbed in the Ge is estimated to be $0.3P$. The cyclotron resonance of electrons and heavy holes outside the drop are labeled EL and H.H. The lines which shift with P are magnetoplasma dimensional resonances of an EHD.

the same for all cavity modes which coupled to the sample.

Figure 2 shows the MDR for sample CR-1 ($l = 1.37$ mm) for a series of laser powers P. Similar spectra were observed for samples of different thicknesses. The field H for the principal MDR line, labeled C in Fig. 2, was measured versus P, simultaneously with I_{709}, for three different focus conditions of the lens F. The results, Fig. 3, show a strong correlation between the MDR and I_{709}.

The MDR can be qualitatively understood as follows. The electron-hole (e-h) plasma drop (here assumed spherical) can act as a small resonator for microwave electromagnetic fields, where the large dielectric constant within the drop reduces the effective wavelength in order to match the diameter of the drop. The coupling of the plasma to an external field H can enhance the dielectric constant, thereby lowering the effective wavelength inside the drop. Thus, as the field is swept, a series of resonances will be observed, corresponding to the standing-wave modes of the resonator. The resonant fields will depend on the radius r of the EHD.

The mathematical problem of finding the normal modes of a plasma sphere in the presence of an applied magnetic field is extremely complicated. For an EHD, which has both hole and electron carriers with tensor masses, the problem has not yet been solved exactly. For the simpler case of a *single carrier* with scalar mass m^*, an exact numerical solution was recently given by Ford and Werner (FW).[4] Their results can be understood by comparison to an approximate but analytic solution to the same problem given by Cardona and Rosenblum (CR)[5] who simplified it by its transverse component

$$\epsilon_T = \epsilon_L\{1 - \omega_p^2/[\omega(\omega \pm \omega_c)]\}, \tag{1}$$

where $\omega_p \equiv (4\pi n_0 e^2/m^*\epsilon_L)^{1/2}$ is the reduced plasma frequency, $\omega_c = eH/m^*c$ is the cyclotron frequency of the carriers, ϵ_L is the lattice dielectric constant ($\epsilon_L = 15.8$ for Ge), and $\pm$ refers to left and right circularly polarized microwaves. With this scalar dielectric function, the problem is solvable. Standing-wave resonances occur for

$$k^1 r = \gamma_{ij}, \quad i = 1, 2, \ldots, \quad j = 0, 1, 2, \ldots, \tag{2}$$

where $k^1 = \omega/c(\epsilon_T/\epsilon_L)^{1/2}$ is the reduced wave vector inside the sphere and γ_{ij} are the roots of a spherical Bessel function.[6] From Eqs. (1) and

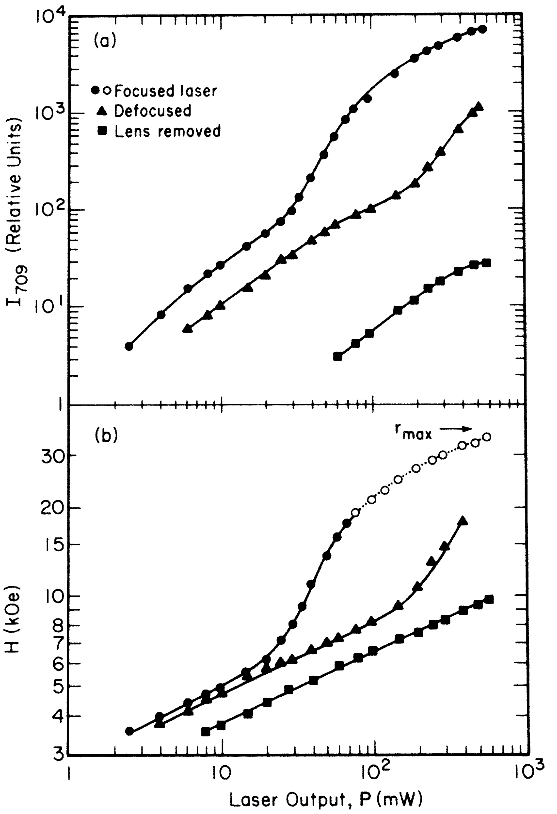

FIG. 3. (a) Drop luminescence intensity versus optical pump power for sample CR-1 at 1.6 K for three focusing conditions. (b) Simultaneously observed resonant field of the principal line C (Fig. 2) of the MDR at $\nu = 25.07$ GHz. The vertical scales of (a) and (b) have the ratio three decades to one, chosen to demonstrate that for $H \gtrsim 10$ kOe, $I_{709} \propto H^3$. The open circles, for H above the magnet range, are scaled directly from the E line (Fig. 2).

(2) we find $\omega_c = \omega - (\omega_p^2/\omega)[1 - (\gamma_{ij}c/\omega r)^2]^{-1}$ or, approximately,

$$H \approx H_c[1 + (r\omega_p/\gamma_{ij}c)^2], \tag{3}$$

where $H_c = m^* c\omega/e$ is the resonant field of the free carriers. The exact solution of FW is similar to Eq. (3) but they find a set of γ_{ij} which are significantly different from the above roots.[7] As $r \to 0$ (i.e., $r\omega_p/c \ll 1$), Eq. (3) should be replaced by $H = 2H_c$.[8,9]

We have solved the more complicated problem of the compensated multicomponent plasma in the EHD in the same approximation as used by CR (scalar dielectric constant).[10] We use the full tensor electron masses of Ge but treat the heavy and light holes as two scalar particles. For $\vec{H} \parallel (001)$ the resulting resonance equation is fourth order in H. We have evaluated it numerically for arbitrary r/γ_{ij}; for large r we find two solutions of interest:

$$H \approx H_c[0.646(\omega_p r/\gamma_{ij}c) \mp 0.0661], \tag{4}$$

where m^* in H_c and ω_p must now be taken as the free-electron mass m_0. For the lowest root, $\gamma_{10} = 2.21$,[7] Eq. (4) becomes

$$H = [(0.0546\ \mu\text{m}^{-1})r \pm 0.588]\ \text{kOe}. \tag{5}$$

Note that for the compensated EHD plasma the resonant field increases linearly, not quadratically, with r. As $r \to 0$, the appropriate solutions of the quartic approach the electron (−) and heavy-hole (+) cyclotron-resonance fields, $H_- = c\omega m_e^*/e$ and $H_+ = c\omega m_{hh}^*/e$. However, in this limit the problem is exactly solvable[11] and we find that the limiting fields approach approximately twice the cyclotron fields: $H = 2.2H_-$ and $H = 1.47H_+$.

It is known[6] that for a single-component plasma the MDR absorption intensity $I \propto r^5$. Our numerical calculation for the EHD yields the same result.

We observe a series of lines (Fig. 2) whose behavior is in reasonable agreement with the above theoretical model. The principal line C and the lower field lines form a series, each of which has exactly the same shape as in Fig. 3(b), but is vertically displaced. We believe these to be the MDR lines of a single EHD. We have observed the same series in several different crystals. In one sample (CR-6, $l = 0.89$ mm) we observed two drops (as exemplified by two distinct series) whose relative size could be varied independently by positioning the laser spot on the crystal. The lines are qualitatively similar to the series predicted by Eq. (4), although one-to-one correspondence in γ_{ij} is not found. This is not too surprising, given the approximate nature of the theory, and the possibility that the drop may not be spherical. A refined theory is being developed. The lines A and B have not yet been classified.

Further evidence supporting the above interpretation is the observation that the resonant fields are linearly proportional to ω, in the range $24 \leq \nu \leq 26$ GHz, in agreement with Eq. (4). The observed intensity of the C line is found to be $I \propto H^{4.5 \pm 1} \propto r^{4.5 \pm 1}$, in agreement with expectation.

Figure 3 shows a striking confirmation of our interpretation: the strong correlation between I_{709} of the drop luminescence and the MDR field of the C line. Since we find $I_{709} \propto H^3$ for large drops, and it is reasonable to expect that I_{709} is proportional to the drop volume, we confirm that

$H \propto r$, as predicted by Eq. (4). The nonlinear behavior of I_{709} and H versus P can be understood: When the drop diameter reaches a significant fraction of the laser-spot size (defined by the focusing condition), the single drop can more efficiently collect the e-h pairs excited by the laser.

For the maximum possible drop radius in this sample, $r_{max} = 0.68$ mm = half the sample thickness, we calculate from Eq. (5) the resonant field $H = 36$ kOe, comparable to the field for the C line at maximum pump power [Fig. 3(b)]. A thinner sample yielded a correspondingly lower maximum resonant field. At the very highest laser pump powers the relative spacing of the lines appears to change, possibly indicating a change in the shape of the drop as its size approaches the sample dimensions. Although earlier experiments[1] reported drop sizes of ~10 μm, recent experiments here[12] report large drops.

Finally, we have used MDR to study decay kinetics of large drops, to be reported separately.[13]

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Negative Magnetoresistance in n-Channel (100) Silicon Inversion Layers

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The transverse magnetoresistance effect of (100) n-channel silicon inversion layers was measured at low temperatures. Negative and/or positive effects have been obtained depending on surface-state density.

Transverse magnetoresistance measurements have been carried out on n-channel metal-oxide-semiconductor field-effect transistors in a temperature range between 2 and 10 K. The oxide thickness was 120 nm and the geometry of the channel (channel length 400 μm, channel width 40 μm) allowed additional information about the Hall mobility. Transistors on a (100) silicon surface were selected so that a wide range in threshold voltage, as well as the corresponding maximum mobility, was represented.

The charge-carrier concentration responsible for the transport in metal-oxide-semiconductor transistors is caused by a sufficiently strong electric field perpendicular to the surface and is confined to the semiconductor region near the Si-SiO_2 interface. As a consequence of the electrical surface field, the energy of the charge carriers perpendicular to the surface is quantized and the carriers behave almost as a two-dimensional electron gas.[1] At sufficiently low temperatures the electrons in an n-channel (100) surface are restricted to the lowest sub-band corresponding to the isotropic effective mass parallel