Observation of Large Long-Lived Electron-Hole Drops in Germanium*

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Alfvén-wave resonances are used to measure time decay of the electron-hole drop radius in stressed Ge, and striking new properties of the condensate are observed. Compared to standard results, the drop volume is larger by more than 1000, and the drop lifetime is increased from 40 μsec to over 400 μsec. We believe the long-lived condensate corresponds to low-density Ge⟨111⟩ or Ge⟨110⟩ phases with one or two electron ellipsoids occupied.

We previously reported excitation of microwave dimensional resonances of large electron-hole drops (EHD) in germanium.[1] These resonances correspond to standing Alfvén waves in a drop of the electron-hole plasma. With standard drops, which we shall call α drops, Alfvén resonances have not yet been observed. We report here the discovery that the large drops displaying Alfvén resonances have a greatly increased lifetime; we call these long-lived drops γ drops.[2] At low temperatures the observed lifetime is of order 400 μsec compared to 40 μsec for α drops.

For equal concentrations of electrons and holes with scalar masses m_e and m_h, the dielectric function is

$$\epsilon(\omega) = 4\pi c^2 n(m_e + m_h)/H^2 \qquad (1)$$

in the limit of $\tau^{-1} \ll \omega \ll \omega_c$, the cyclotron frequency. Here n is the electron-hole density of the drop and H is the externally applied field. This leads to the dispersion relation for Alfvén waves,[3]

$$\omega^2 = c^2k^2/\epsilon(\omega) = H^2k^2/4\pi n(m_e + m_h). \qquad (2)$$

For an isotropic spherical plasma of radius R, the resonance condition is $kR = \gamma_{ij}$, where γ_{ij} given in Ref. 1 are approximately the roots of a spherical Bessel function. At constant frequency the resonant fields of the modes of the EHD sphere are directly proportional to the radius:

$$H(ij) = [4\pi n\omega^2(m_e + m_h)/\gamma_{ij}^2]^{1/2}R \equiv \Gamma R. \qquad (3)$$

For $\omega = 1.6\times 10^{11}$ sec^{-1}, $m_e + m_h \simeq 0.4m$, and $\gamma_{11} = 3.25$, a resonant field $H(11)$ of 20 kOe corresponds to $R = 0.13$ mm for $n = 2.2\times 10^{17}$ cm^{-3} and to $R = 0.23$ mm for $n = 0.7\times 10^{17}$ cm^{-3}. We observe magnetic dipole modes with currents circulating throughout the drop; thus, it would be impossible for a cloud of small drops to display the observed sharp resonances, with $\omega\tau$ as high as 30. These radii are over an order of magnitude larger than the α-drop radii previously measured by Rayleigh scattering,[4] where $R \leq 10$ μm.

We observe the decay of the resonant fields $H(ij)$ and of the EHD luminescence intensity after the excitation light is switched off. Because the drop radius is proportional to $H(ij)$, the Alfvén resonances provide a unique probe of the drop kinetics. In our microwave experiments the pure Ge samples ($N_A = 10^{11}$ cm^{-3}) are disks of diameter 3.9 mm and thickness 1.4 mm (sample CR1) and 1.65 mm (sample CR3) mounted without metal contacts and stressed in a dielectric holder by a nylon set screw. No Alfvén resonances are observed when the stress is removed.

The experimental arrangement is described in Ref. 1, with the lockin detector replaced by a boxcar integrator. The laser excitation is switched on for 2 msec and off for 30 msec, with 10-μsec risetime. The boxcar gate of width 10 μsec or less is swept slowly from a delay of zero to 4 msec after the light is switched off. A series of microwave-absorption modes (Fig. 1) is observed up to 2 msec after the excitation light is removed; the time delay of these modes depends on the external magnetic field. These absorption modes correspond to the previously observed Alfvén resonances. As the drop radius decays a resonance is observed whenever $H(ij) = H$. Assuming the form $H(ij) = \Gamma R_0 \exp(-t/3\tau_d)$, we find from Fig. 1 that $\tau_d = 615$ μsec.

Direct confirmation of enhanced lifetimes is obtained from the decay of the drop luminescence spectrum after the light is switched off, Fig. 2. This experiment, performed under somewhat different stress conditions, yields $\tau_d = 350$ μsec at $T = 1.8$ K. The lifetime increased from 350 to 600 μsec as the incident light intensity was reduced from 100 to 0.1 mW. We have observed the simultaneous decay of the luminescence and

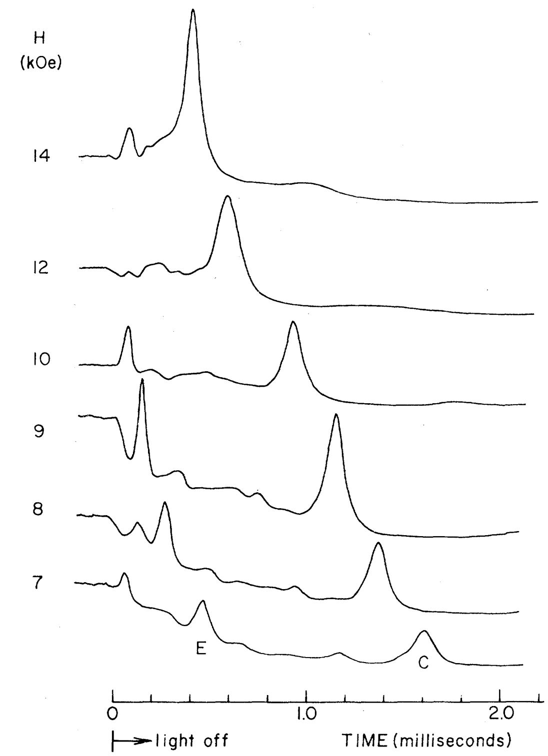

FIG. 1. Microwave absorptions following a 2-msec square laser pulse ($P \approx 400$ mW) for several external magnetic fields H. The modes labeled C and E correspond to two of the Alfvén resonances reported earlier, Ref. 1. The drop radius decays as $R = R_0 \exp(-t/3\tau_d)$, and absorption modes are observed whenever $H(ij) = H$. These data for sample CR1 at $T = 1.5$ K yield $\tau_d = 615$ μsec. The gain in the lower three traces is 2.5 times the gain in the upper three; and $\omega = 1.585 \times 10^{11}$ sec^{-1}.

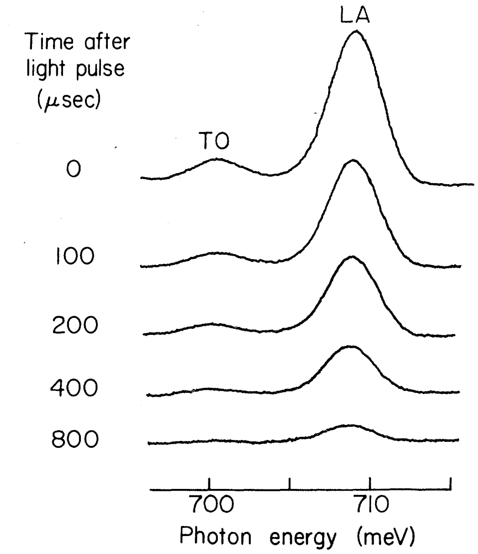

FIG. 2. Decay of the luminescence spectrum for sample CR1 after the light pulse, showing the long drop lifetime, $\tau_d = 350$ μsec at $T = 1.8$ K, $H = 0$, and $P \approx 440$ mW. The vertical deflection varies linearly with signal intensity. The spectrometer is calibrated to ± 2 meV, with a resolution of 2.5 meV.

Alfvén resonances, and in Fig. 3 we plot I_{lum} versus $[H(ij)]^3$ of the C line. The linear dependence for $H(ij) > 10$ kOe confirms the simplified relations $I_{\text{lum}} \propto R^3$ and $H(ij) \propto R$ for these high fields. Deviations are found for $H(ij) < 10$ kOe, to be reported later.

We have also produced these long-lived drops in a variety of samples using a variable-stress holder with up to 20 kg applied to a cylindrical plunger of cross section 2.4 mm^2; experiments are in progress to determine the dependence of I_{lum}, τ_d, and the luminescence spectrum on stress, temperature, and sample geometry. Our preliminary results are (1) the total drop luminescence from the sample is a maximum when the laser is focused to a point near the plunger, indicating that the γ drop is formed near the region of maximum stress; (2) for stress along $\langle 110 \rangle$ the luminescence spectrum of the γ drops is shifted toward lower photon energy by up to 5 meV, depending on the stress; (3) enhanced

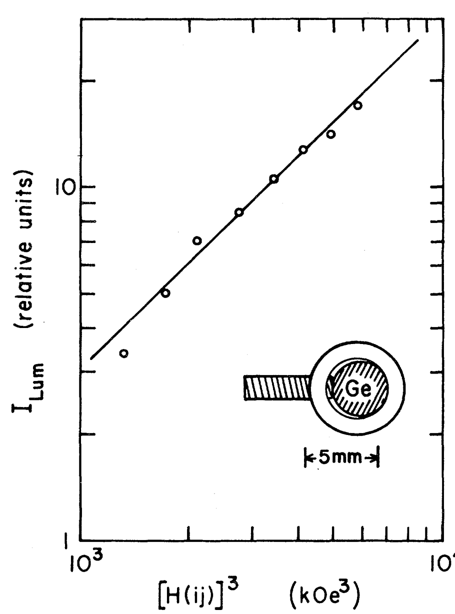

FIG. 3. Intensity of the LA-phonon– assisted drop luminescence versus the cube of the Alfvén field of the C line, measured simultaneously after the laser light is switched off. Here, $P \approx 70$ mW and $T = 1.8$ K. The straight line has slope 01.0. Insert, Kel-F crystal holder. Stress is applied to the sample along $\langle 110 \rangle$ by the nylon set screw.

lifetimes are also observed at 4.2 K, where α-drop lifetimes are considerably shortened by increased evaporation of electron-hole (e-h) pairs; (4) no γ drops are formed when the stress is removed and reapplied at helium temperatures, unless great care is taken to apply the stress via a "soft" plastic interface which minimizes the high-stress points at surface irregularities. Otherwise, when the stress is reapplied at He temperatures, the luminescence intensity and lifetime decrease, consistent with results reported[5,6] for α drops.

The long lifetime of γ drops suggests that the e-h density is significantly lower than the density in the α phase in unstrained Ge. We expect the radiative lifetime to vary as n^{-1} and the nonradiative[7] Auger lifetime to vary as n^{-2}. The e-h density in the condensate in unstressed Ge is close to 2.2×10^{17} cm^{-3}, by experiment and by calculation. Here four conduction-band ellipsoids and two valence bands are populated; the configuration is described as Ge(4:2). For a ⟨111⟩ uniaxial stress near 3 kg mm^{-2} only one electron ellipsoid and two hole ellipsoids are populated[5,6]; the e-h density[8] decreases by the factor 0.32 to $n = 0.65\times 10^{17}$ cm^{-3}, and r_s increases from 0.6 to 0.9. The radiative and nonradiative lifetimes are expected to increase: $\tau_R(\gamma)/\tau_R(\alpha)\approx 3$ and $\tau_{NR}(\gamma)/\tau_{NR}(\alpha)\approx 10$.

The strong ⟨111⟩ stress limit, usually called Ge⟨111⟩, is reached near 10 kg mm^{-2}. The configuration here is Ge(1:1), with only one electron ellipsoid and one hole ellipsoid populated. Vashishta, Das, and Singwi[9] calculate $r_s = 1.6$ and $n = 1.11\times 10^{16}$ cm^{-3}. Thus for the Ge(1:1) configuration we expect $\tau_R(\gamma)/\tau_R(\alpha)\approx 20$ and $\tau_{NR}(\gamma)/\tau_{NR}(\alpha)\approx 390$. Up to the present our γ drops have been formed in the nonuniform strain field near the point of application of a local stress, usually ⟨110⟩. We believe the drops are in a mixed configuration. There appears to be no difficulty in accounting for the observed lifetime enhancement of 10 to 20 on this model; the large drop size follows directly from the kinetics. Experiments show a clear threshold stress for the formation of γ drops even in this nonuniform (but convenient) geometry. We have a preliminary observation of the narrowing of the luminescence line near 709 meV in the γ drops. With no allowance made for the nonuniformity of the strain across the drop, we infer $n(\gamma)/n(\alpha)\leq 0.30$ on the Fermi-energy model of the linewidth.

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[1]R. S. Markiewicz, J. P. Wolfe, and C. D. Jeffries, Phys. Rev. Lett. 32, 1357 (1974), and 34, 59(E) (1975). We now have experimental evidence that strain, fortuitously introduced by the sample holder in these microwave experiments, is necessary for the production of large drops displaying Alfvén resonances. Furthermore, in our experiments to date, an inhomogeneous strain appears to be required.

[2]We distinguish γ drops from large drops obtained in unstressed Ge under intense laser excitation [R. M. Westervelt, T. K. Lo, J. L. Staehli, and C. D. Jeffries, Phys. Rev. Lett. 32, 1051 (1974); A. Nakamura and K. Morigaki, Solid State Commun. 14, 1213 (1974); R. W. Martin, to be published], and also from hemispherical clouds of small droplets: M. Voos, K. L. Shaklee, and J. M. Worlock, Phys. Rev. Lett. 33, 1161 (1974); R. W. Martin, to be published; the results of B. J. Feldman, Phys. Rev. Lett. 33, 359 (1974), are now interpreted as a sharp-edged cloud of small droplets, the observed lifetime being 40 μsec.

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[7]We are indebted to W. F. Brinkman for this helpful suggestion about the three-particle decay process.

[8]P. Vashishta, private communication; M. Combescot and P. Nozières, J. Phys. C: Proc. Phys. Soc., London 5, 2369 (1972), calculated the density in the Ge(1:2) configuration to be 0.51 of that in the Ge(4:2) configuration.

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