COMMENTS AND ADDENDA

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Investigation of the shape of a cloud of electron-hole droplets in germanium

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Absorption and scattering of light are used to investigate a cloud of electron-hole drops in Ge at 2°K. We find a drop size of 2 μm, from light scattering; and use an Abel transform to unfold the absorption data and obtain a complete droplet density map. The cloud is distinctly nonspherical. The droplet penetration in a direction perpendicular to the surface of excitation is 1.5 times greater than that in a parallel direction. This result is discussed in terms of alternative models for cloud formation.

It is well known that under the proper conditions, excitons in germanium condense into a liquid-plasma phase as predicted by Keldysh.[1] Many experiments have demonstrated that the condensate appears in the form of a macroscopic cloud of small (2–10 μm) droplets,[2] which are generally called electron-hole drops (EHD). The most compelling and fruitful experimental technique for measuring properties of the EHD cloud, such as droplet sizes and spatial distributions, has been scattering and absorption of infrared light. Theoretical understanding of the mechanisms which determine these properties is at present very sketchy, particularly for the case of surface optical excitation of the nonequilibrium excitons or electron-hole pairs.

Recently Voos, Shaklee, and Worlock[3] studied the EHD cloud formed in Ge at ~2 K under rather high steady-state surface excitation. They measured the attenuation and scattering of an infrared laser beam at wavelength 3.39 μm, in an experiment represented in Fig. 1. The crystal was excited with a spot-focused Ar^+ laser beam, of 50-mW power at 5145 Å. By probing in the symmetry plane $y=0$ as a function of the depth x, and assuming hemispherical symmetry, they concluded that the EHD density was uniform inside a hemispherical cloud of radius ~1 mm, and fell off very rapidly to zero outside. The measured droplet density was $\sim 10^9$ cm^{-3}, and the EHD size was also uniform with radius ~2 μm.

The present work is an extension of and improvement over that of Voos, Shaklee, and Worlock. By probing also as a function of the height y, we are able to relax the symmetry assumption from hemispherical to cylindrical, with symmetry axis x perpendicular to the pumped surface, and centered on the pumped spot. We then use an Abel Transform[4] to obtain a complete three-dimensional density map for the EHD cloud. We find a cloud shape which is distinctly nonspherical, the constant-density contours being elongated along the symmetry axis. In addition, the density varies significantly within the cloud, and the edges are

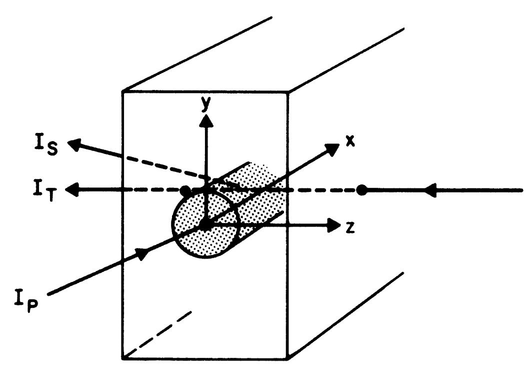

FIG. 1. Diagram of experiment to study EHD cloud in Ge. Pump beam I_P (50-mW cw 5145 Å) spot-focused on crystal surface at origin of coordinates as shown. Probe beam I_0 (2 mW, 3.39 μm, resolution ~ 100 μm); scattered and transmitted components I_S and I_T measured as function of depth x and height above the symmetry axis y.

not sharp.

We present and analyze here measurements of attenuation of the probe beam. Scattered-light measurements were used only to verify that the EHD radii were 2 μm.

The attenuation $A(x, y) = -\Delta I_T/I_T$ is related to the EHD density $\rho(x, y, z)$ by

$$A(x, y) = C \int_{-\infty}^{\infty} \rho(x, y, z)\, dz , \qquad (1)$$

where the constant C, following the work of Worlock, Shaklee, Damen, and Gordon,[5] is 2×10^{-10} cm^2.

To make further progress, we analyze the signal as follows. Cylindrical symmetry allows us to rewrite the integral in Eq. (1) as

$$A(x, y) = 2C \int_{y}^{\infty} \frac{\rho(x, r) r\, dr}{(r^2 - y^2)^{1/2}} , \qquad (2)$$

where $r = (y^2 + z^2)^{1/2}$; and the Abel Transform[4] enables us to evaluate the density function $\rho(x, r)$:

$$\rho(x, r) = -\frac{2}{\pi r C} \frac{d}{dr} \int_{r}^{\infty} \frac{A(x, y) y\, dy}{(y^2 - r^2)^{1/2}} . \qquad (3)$$

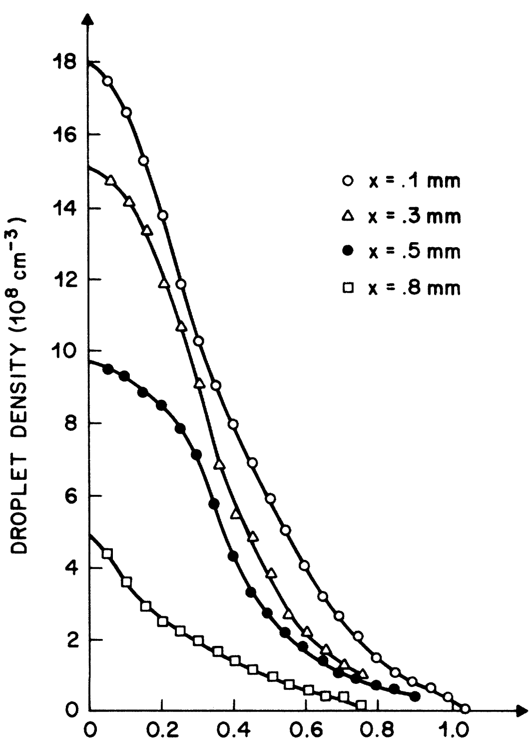

FIG. 2. Droplet densities calculated by Abel transform, plotted as a function of r, the radial distance from the cylindrical symmetry axis. Different curves correspond to different depths x beneath the pumped surface.

Computer calculations of the density $\rho(x, r)$ from Eq. (3) are shown in Fig. 2. Clearly these are not the density functions of a hard-edged cloud. Finally, in Fig. 3, we show density contours, or plots in an x, r plane of lines of constant density. These contours show that the penetration of EHD is significantly greater along the symmetry axis than laterally. For instance, the contour at EHD density of 6×10^8 cm^{-3} is approximately $1\frac{1}{2}$ times as long as it is wide.

We wish to present now a brief discussion of the possible models which can be invoked to explain EHD cloud configurations, and how our measurements limit the choice.

1. Free-particle diffusion model. In this model, excitons and free electron-hole pairs diffuse independently from the surface into the interior of the crystal, where they condense. Although exciton diffusion lengths of ~1 mm are reasonable, this model is unattractive because it is hard to believe the anisotropic diffusion implied by our results. In addition, it is likely that under steady-state conditions, the diffusing species must interact with the condensed droplets, so that independent diffusion is not possible.

2. Ballistic EHD model. In this model, postulated by Combescot[6] and discussed by Damen and Worlock,[7] EHD formed near the surface with some initial velocity drift ballistically outwards, slowing down by interaction with excitons, impurities, or phonons. Clearly the cloud shape found experimentally forces this model to provide anisotropy either in the initial velocity distribution or in the braking mechanism. We note that the region of primary excitation is pancake shaped, being approximately 1 μm deep and 100 μm in diameter. Electron-hole pairs streaming out of this excita-

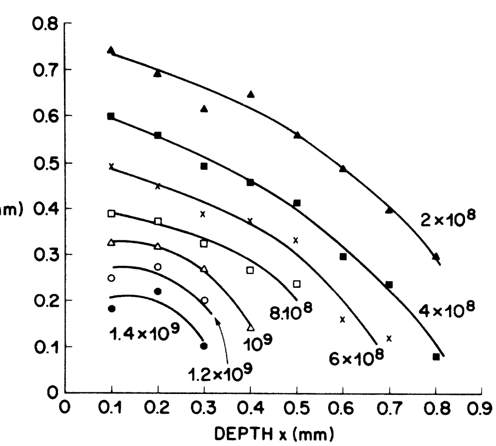

FIG. 3. Contour plots of droplet densities. Each curve is labeled by its droplet density (droplets/cm^3). Symmetry about the x axis is assumed.

tion region coherently, as a liquid, for example, will have a velocity distribution peaked in the direction perpendicular to the plane of the pancake. The spatial distribution can be interpreted in terms of memory of this early velocity distribution.

3. Wind models. In these models, EHD which begin their life cycle near the surface are pushed into the crystal by either an exciton wind[8] or a phonon wind[9] which exerts a gentle pressure outward, away from the center of excitation. Once again, our results require these pressures to be anisotropic. The crystal itself we know to be not isotropic but cubic. Although free-particle diffusion and the exciton wind are not likely to be affected, the elastic properties are distinctly anisotropic and hence the phonon wind could well be nonspherical.

This qualitative discussion indicates several directions of further inquiry: (i) the effect of exciting spot size on the cloud shape; (ii) the effect of crystal orientation on the cloud shape; (iii) the dependence of cloud shape on exciting wavelength, since shorter wavelengths generate more phonons than longer; and (iv) the direct measurement of EHD velocities in the cloud.

Finally, the difference between our results and those of Voos, Shaklee, and Worlock indicates that cloud properties can be sample dependent, which tells us perhaps that motion into the interior is inhibited by structural or chemical defects.

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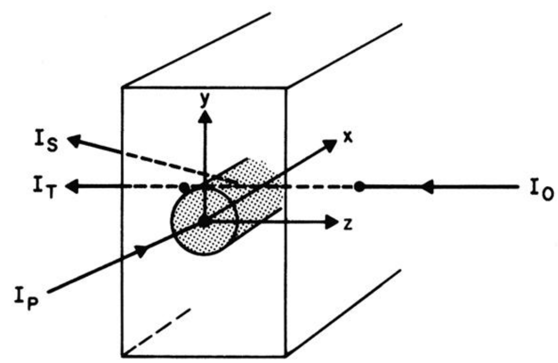

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