Observation of Large Electron-Hole Drops in Germanium*

Bernard J. Feldman
Department of Physics, University of California, Berkeley, California 94720
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This Letter reports the first direct observation of electron-hole drops (EHD) in germanium. An intense, focused laser beam creates a single, large EHD, whose shape and size are determined by the spatial distribution of its luminescence. The observed drops are spherical in shape with radii that increase from 0.25 mm to over 1 mm with increasing laser power. These results confirm size measurements of the EHD by recent decay-kinetics and dimensional-resonance studies.

This Letter reports the first direct observation of electron-hole drops (EHD) in germanium. An intense, focused laser beam creates a single, large EHD, whose size and shape are determined by the spatial distribution of its luminescence. The observed drops are spherical in shape with radii that increase from 0.25 mm to over 1 mm with increasing laser power. Previously, the drop size was inferred by Rayleigh scattering,[1,2] charge pulses in p-n junctions,[3,4] far-infrared absorption,[5] and cyclotron resonance[6]; these experiments gave drop radii from 1 to 20 μm. Very recently, decay-kinetics[7] and dimensional-resonance[8] studies suggested the existence of large EHD radii of the order of 0.2 mm; those latest drop-size measurements are confirmed by this work.

The experimental procedure consists of the following[9]: A 2-W Ar-Kr ion laser beam is focused onto the germanium samples by a lens mounted on an x-y micrometer translator. The two samples used are 2.5-cm-diam disks with thicknesses d of 0.5 and 1.0 mm of very high-purity p-type Ge[10] which are optically polished and etched in a CP-4 solution. The crystals are mounted on an aluminum flange with a 0.15-mm-thick vertical slot (see Fig. 1), and then immersed in liquid He in an optical cryostat. The EHD recombination luminescence (709 meV) that passes through the slot is collected and focused onto the entrance slit of a monochromator, and then collected from the monochromator exit slit and focused onto a Ge photodetector, in an arrangement similar to that previously reported.[11]

The theory behind this experiment is very straightforward. The translating lens moves the focused laser beam—and with it the one large EHD—across the vertical slot. If the drop radius is much greater than the slot width, the EHD luminescence through the slot, I, is proportional to the cross-sectional area of the drop subtended by the slot (see Fig. 1). For a spherical drop of radius R and a lens position x, measured from the center of the slot, $I(x) \propto R^2 - x^2$ for $|x| \leq R$, and $I(x) = 0$ for $|x| > R$. The volume of the drop, V, is proportional to $\int_{-\infty}^{\infty} I(x)\,dx$, and the cross-

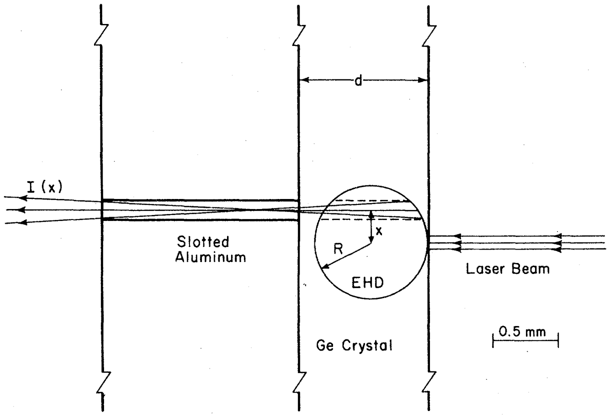

FIG. 1. Schematic diagram of the Ge sample and sample holder showing the optical geometry of the experiment.

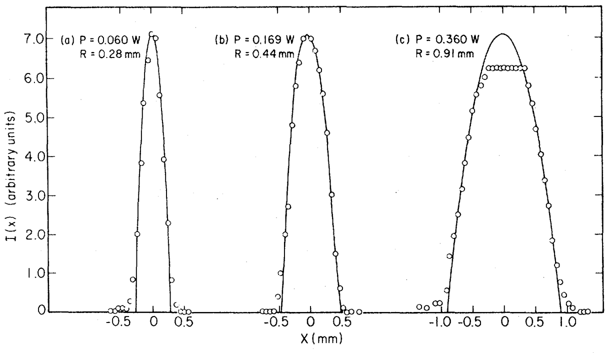

FIG. 2. The luminescence intensity I as a function of the lens position x for three laser powers P. The circles are the experimental points; the solid line is the theory $I(x) \propto R^2 - x^2$. The sample temperature is 2.0°K and the sample thickness is 1 mm.

sectional area of the drop, A, is proportional to $I(x=0)$.

A typical spectrum of $I(x)$ is shown in Fig. 2(a). The circles are the experimental points, and the solid line is just the function R^2-x^2, with $R=0.28$ mm chosen for the best fit to the data. Even without a slit function folded into the theory, the agreement between theory and experiment is excellent.

As the laser power P is increased,[12] the drop radius increases as shown in Figs. 2(b) and 2(c). A plot of $R(P)$ for the $d=1$-mm sample is given in Fig. 3, which also includes the experimental values of $V^{1/3}(P)$ and $A^{1/2}(P)$. The fact that $R(P)$, $A^{1/2}(P)$, and $V^{1/3}(P)$ have the same dependence on P, namely $P^{0.4\pm0.1}$, is further evidence that the drop is spherical.

The interesting behavior of $I(x)$, R, and $A^{1/2}$ at high values of P is due to the fact that the drop diameter becomes greater than the sample thickness. Then the EHD growth is limited by the sample surfaces in one direction and expands in the other two dimensions; the drop keeps its density fixed and starts to resemble a pancake. The flattening of the peak of $I(x)$ in Fig. 2(c) is just the flattening of the pancake. The relative decrease in $A^{1/2}$ and increase in R in Fig. 3 correspond to the bounded growth of the drop in one dimension and the increased expansion in the other two. Notice that the divergence in $A^{1/2}(P)$ and $R(P)$ starts approximately at $R=0.5$ mm, one half of the sample thickness. In the $d=0.5$-mm sample, this behavior starts at $R=0.25$ mm.

The free-exciton (FE) luminescence (714 meV) is unobservable at 2.0°K because the FE equilibrium concentration is so low at that temperature.[11] However, at 4.2°K both the FE and EHD luminescence are observed as shown in Fig. 4. The spatial distribution of the FE has an exponential behavior characteristic of a diffusion process and is in sharp contrast to that observed for the EHD.

These experimental results are inconsistent with the idea of a gas of small EHD. The spatial distribution of such a gas would follow that of the FE gas, namely exponential in shape and relatively insensitive to P. This model cannot explain the observed spherical distribution, its expansion with increasing P, and its interaction with the back surface of the crystal. All these results strongly suggest the existence of one large, spherical EHD.

There is one primary reason why such large single drops are created in this experiment: An intense laser beam of the order of 0.1 W that is

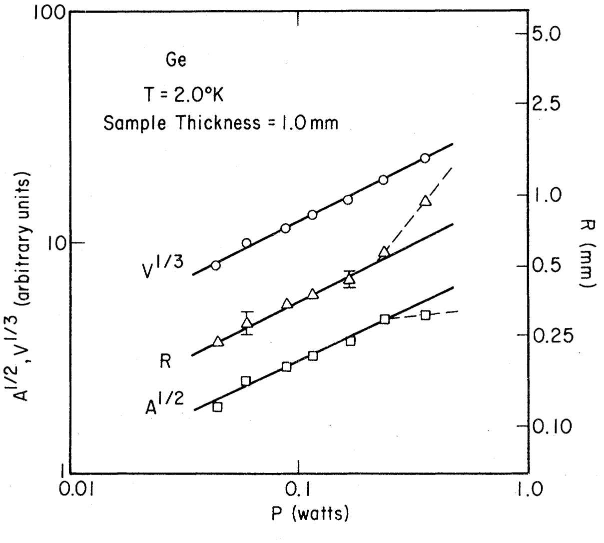

FIG. 3. The experimental values of the EHD radius R, area A, and volume V as a function of the incident laser power P.

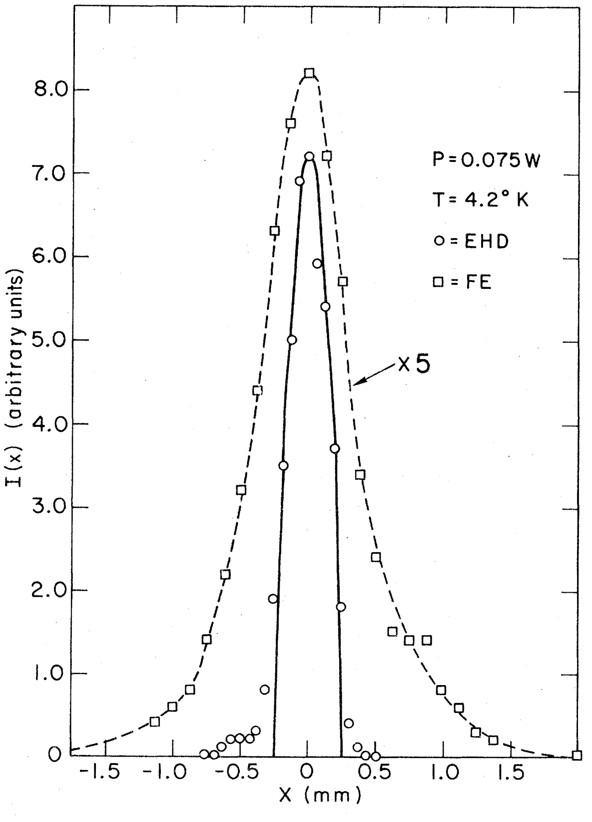

FIG. 4. The FE and EHD luminescence intensity I as a function of the lens position x. The solid line is the EHD line-shape theory with $R=0.25$ mm.

well focused to a spot size of about 0.1 mm×0.1 mm creates an extremely high and localized concentration of free excitons that can condense into one large drop. Many of the previous experimenters[1-6] that measured much smaller drop sizes worked with lower light intensities and larger spot sizes which could create many small drops instead of one large drop.

There is one serious problem with this large EHD model: The maximum drop radius calculated from knowing the incident laser power[13] is approximately one half of that measured by fitting $I(x)$. There are a number of possible explanations for this disagreement: (1) an underestimation of the laser power or its electron-hole conversion efficiency; (2) an overestimation of the drop radius; (3) the existence of voids inside the EHD occupied by free excitons; (4) an enhancement of the EHD lifetime for such large drops; or (5) some combination of the above. This question is being presently investigated.

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[9] A similar experimental technique was employed by Y. E. Pokrovskii and K. I. Svistunova, Fiz. Tverd. Tela 13, 1485 (1971) [Sov. Phys. Solid State 13, 1241 (1971)]; C. Benoît à la Guillaume, M. Voos, and F. Salvan, Phys. Rev. Lett. 27, 1214 (1971); R. W. Martin, Phys. Status Solidi (b) 61, 223 (1974). However, our observations and conclusions are quite different.

[10] The samples used in this work are from the same boule as samples 145A and 145B of T. K. Lo, B. J. Feldman, and C. D. Jeffries, Phys. Rev. Lett. 31, 224 (1973).

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[12] The laser power absorbed by the Ge crystal is approximately 36% of P (Figs. 2 and 3), as a result of losses in the optics and reflection from the Ge surface. For $P=0.1$ W, the calculated sample heating is less than 0.1°K.

[13] The maximum radius is calculated by assuming that each absorbed photon creates one electron-hole pair, all of which condense into one drop with a density of 2×10^{17} electrons/cm^3 and a lifetime of 3.5×10^{-5} sec (Ref. 7).

Model for Electroluminescence in GaN

J. I. Pankove and M. A. Lampert
RCA Laboratories, Princeton, New Jersey 08540

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A model to explain dc electroluminescence in GaN diodes is presented. The voltage applied to the diode is partially localized at sharp points and ridges at the cathode. Electrons, tunnel-injected into the active material at the points and ridges, gain sufficient kinetic energy in the high field to cause impact excitation of the luminescent center either directly or indirectly (electron-hole–pair impact excitation across the GaN gap with subsequent hole capture by the luminescent center).

Electroluminescence (EL) from GaN diodes without p-n junctions has previously been reported,[1] but the mechanisms of charge transport, excitation, and de-excitation were not clearly understood. More recent work has made possible new insights into the properties of GaN m-i-n (metal–insulator–n-type) diodes.

The GaN EL diodes are made by a technique described earlier[2]: First, undoped n-GaN is grown by chemical vapor deposition[3] onto a sapphire