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Prepared for the U. S. Department of Energy
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MOTION OF ELECTRON-HOLE DROPS IN Ge

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Using a new experimental technique based on hysteresis, the time development of the size of a localized packet of electron-hole drops (EHD) in a spatially uniform free exciton gas near threshold is measured for times ~10^4 sec. No significant motion is found, determining an upper limit $D \lesssim 10^{-9} cm^2 sec^{-1}$ to the possible EHD diffusion constant.

The transport of electron-hole drops (EHD) in Ge has been extensively investigated in past years.[1] A variety of experiments[1] have shown that EHD rapidly move ~1 mm from a localized excitation spot and form a "cloud" of small droplets, apparently propelled by the "phonon wind."[2] Other experiments[1] have shown that EHD can be easily moved by an applied non-uniform strain or an electric field. However, the persistence of hysteresis effects[3,4] near threshold for times[4] ~10^4 sec seemed to indicate that EHD could remain stationary for comparably long times. Using a new experimental technique we have discovered that EHD in suitably unperturbed crystals of ultrapure Ge are virtually immobile at 2K.

The experimental method is illustrated in Figs. 1 and 2. Using the hysteresis effect,[3,4] a spatially uniform free exciton (FE) gas is produced inside a large (8x8x4 mm^3) crystal of ultra-pure Ge by volume excitation with 1.5 μm wavelength radiation, as indicated in Fig. 1. The excitation level ($P = 2.4$ mW cm^{-2} for Fig. 2) is chosen below the threshold for EHD formation, but above that for drop breakup; thus the presence of EHD depends upon the history of excitation. First the volume excitation is monotonically increased to P, so the system initially contains no EHD, as confirmed by spatially resolved scans of the luminescence intensity I_{EHD} and I_{FE} vs. horizontal position x inside the crystal, shown in Figs. 2a and 2b. A localized packet of EHD is then produced by additional momentary stripe excitation from an Ar ion laser as indicated in Fig. 1. During stripe excitation EHD are ejected from the excited region as in earlier work[1] (P_{stripe} ~ 70 mW cm^{-1}) and form the cloud of droplets shown in Fig. 2c. After stripe excitation has ceased, individual EHD remain due to hysteresis,

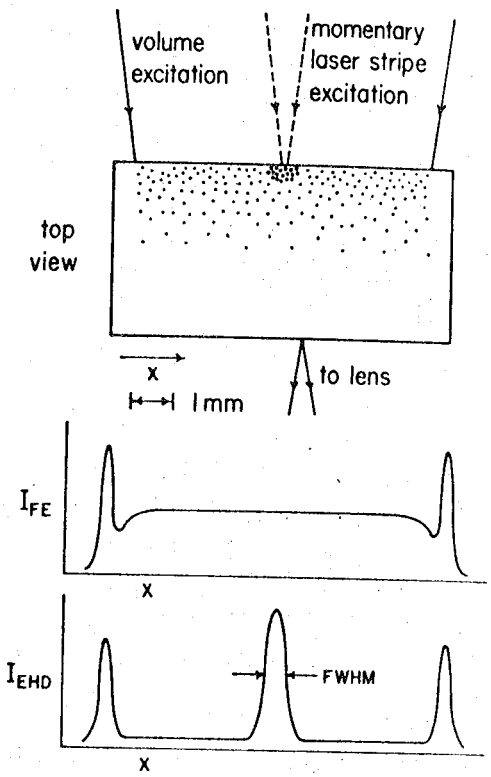

Fig. 1. Excitation geometry of Ge sample, to scale, showing spatial distribution of EHD and FE.

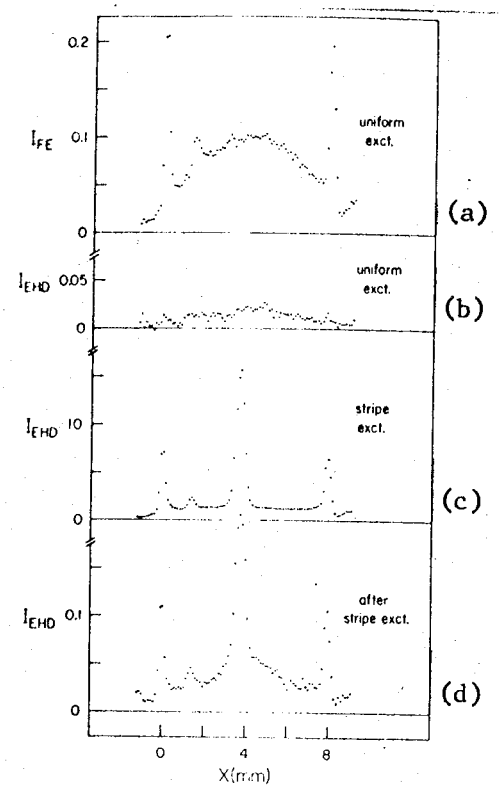

Fig. 2. Scans of the luminescence intensities I_{EHD} and I_{FE} at 2.10K under various conditions.

and give the spatial profile shown in Fig. 2d. Thus a localized packet of drops is produced in a spatially uniform system by a non-uniform history of excitation. Note that, in principle, individual EHD can survive indefinitely at any horizontal position x inside the crystal. From I_{FE} and I_{EHD} in Fig. 2 we estimate that the rate of decay of e-h pairs as EHD inside the packet is roughly ten times less than the decay rate of FE. Thus the presence of EHD is only a small perturbation on the system, unlike previous experiments on EHD motion.[1] The very slow time development of the spatial distribution of EHD is obtained by repeatedly recording the spatial profile of the EHD luminescence for times $t \sim 2\times10^4$ sec.

A series of scans of the EHD luminescence profile at various times t following the end of stripe excitation is shown in Fig. 3; note that the horizontal scale is expanded and shifted by ≈4 mm compared with Fig. 2. The most striking feature of this data is that the EHD spatial distribution at $t = 1.66\times10^4$ sec is nearly identical to that at t = 660 sec. During this time the peak intensity decreases

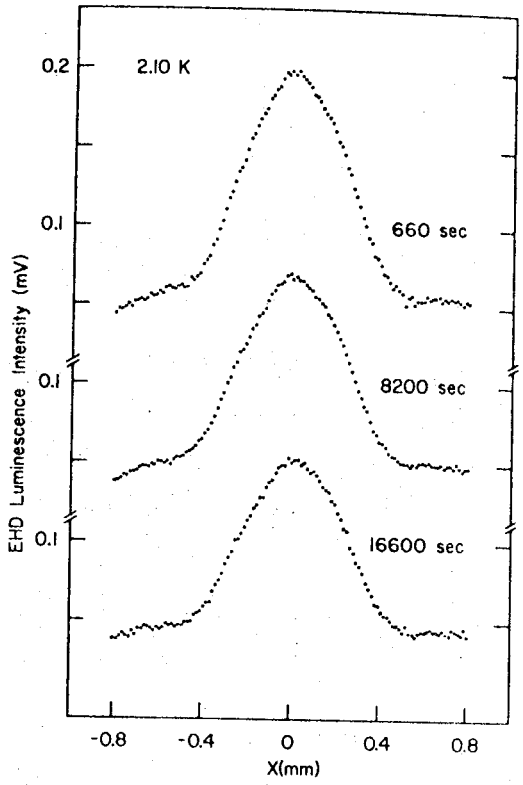

Fig. 3. Scans of the EHD spatial profile at 2.10K at various times after stripe excitation.

slightly, but neither the full width at half maximum $\Delta x(t)$ nor the horizontal position of the distribution changes by more than ≈ 20 μm, roughly the limit of stability of our apparatus. If EHD undergo diffusion, one would expect the distributions in Fig. 3 to broaden in time according to

$$\Delta x(t)^2 = \Delta x(0)^2 + (16\ln 2)Dt \qquad (1)$$

where D is the possible EHD diffusion constant. Using Eq. 1, we find from the data of Fig. 3 that $D \lesssim 10^{-9}\mathrm{cm}^2\mathrm{sec}^{-1}$ at 2.1K, a value 5 to 11 orders of magnitude smaller than previous experimental estimates.[5] The extreme smallness of D in this crystal indicates that EHD must be pinned to lattice defects in the absence of an applied force. The strongest damping mechanism other than defects, phonon scattering, is theoretically predicted to be $D_p \gtrsim 10^{-4}\mathrm{cm}^2\mathrm{sec}^{-1}$ for EHD at 2K.[1] Once sufficient force is applied to EHD pinned to defects, one expects that they break loose and travel through the crystal with a mobility corresponding to D_p above, as observed by Alekseev et al.[5]

The crystal used to obtain Figs. 2 and 3 was detector-quality ultrapure Ge, essentially free of deep traps for free carriers; the net concentration of shallow impurities was $|N_A - N_D| \approx 1.8\times10^{10}\mathrm{cm}^{-3}$ and the dislocation density was $N_{dis} \sim 500\ \mathrm{cm}^{-2}$. In order to test the effectiveness of dislocations as pinning centers for EHD, an undislocated crystal was also investigated, with $|N_A - N_D| \approx 2\times10^{11}\mathrm{cm}^{-3}$, due to 80 meV deep acceptor levels.[6] This crystal gave results similar to Figs. 2 and 3, except that the EHD cloud created by stripe excitation was much wider (Δx = 2.8 mm for $P_{stripe} \sim 40\ \mathrm{mW\ cm}^{-2}$) and exhibited structure due to anisotropies in the shape of the EHD cloud

as discovered by Greenstein and Wolfe.[7] As for Fig. 3, no significant broadening or motion of the EHD cloud was observed for times up to 1.6×10^4 sec, determining the upper limit $D \lesssim 10^{-8}\,cm^2 sec^{-1}$ to the EHD diffusion constant at 2.1K for this crystal. Thus the EHD pinning centers are defects other than dislocations. The most likely candidates are neutral impurity atoms, to which EHD theoretically bind by 5 to 7 meV per atom.[8]

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