MOTION OF ELECTRON-HOLE DROPS IN Ge AT LOW EXCITON DENSITIES

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ABSTRACT

The expansion of the electron-hole drop (EHD) cloud after a short and local excitation by a pulsed dye laser is investigated by EHD detection in a metal-semiconductor contact. In regions with low free exciton (FE) densities a free flight of the drops is observed, suggesting a collision time of EHD $\tau_c \geq 25\mu$sec. It is proposed that the EHD are ejected out of the excitation region by a strong FE density gradient. Velocities in the range 200 - 2000 cm/s are observed independently of an applied electric field, indicating the EHD to be essentially uncharged.

I. INTRODUCTION

In order to reveal the dynamics of the exciton condensation occurring in Ge at low temperatures it is of importance to know the detailed conditions for nucleation and growth of the electron-hole drops (EHD) formed. The excitation by an intense laser beam being usually very local, these conditions depend strongly on the possible motion of EHD. Thus giant drops have been formed recently by applying an inhomogeneous stress field forcing the drops towards the point of maximum stress.[1] In the absence of external fields, on the other hand, experiments[2,3] show a sharp boundary of the EHD cloud from a local excitation, indicating negligible drop diffusion. Hence, the spatial distribution of EHD previously reported[4-6] is governed mainly by free exciton diffusion in connection with a finite growth rate of the liquid drops.[6,7]

In the present work is discussed some experiments revealing real EHD motion in a region with a low FE density. The analysis of the

results suggests a revised view on diffusive motion of EHD as well as on their drift mobility.

II. EXPERIMENTAL PROCEDURE

In the present experiment Ge samples (2.7 Ωcm, n-type), at 2 K, were excited by a pulsed dye laser emitting at 6200 Å and with a peak power of 50 W. Pulse width and repetition rate were 10 nsec and 20 Hz, respectively. The experimental geometry is shown in Fig.1. The

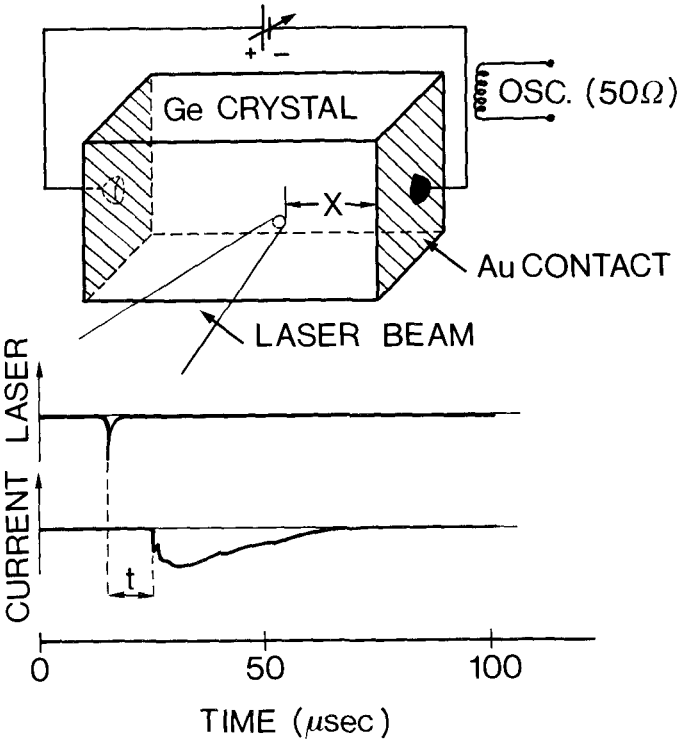

Fig.1. Experimental geometry and oscilloscope traces of laser light pulse (upper trace) and typical photocurrent signal (lower trace). The delay time t depends only on the distance x between laser spot and negative contact.

samples ($0.6 \times 0.6 \times 0.6$ mm^3) were supplied with Au contacts symmetrically on two opposite faces, and a bias voltage of 0-5 V was applied across the sample. The transient photocurrent was monitored via a current transformer and displayed on the oscilloscope. The laser beam was sharply focussed on the surface of the sample and it could be moved

along the sample in a direction perpendicular to the contact planes. The laser pulse and a typical photocurrent signal is also displayed in Fig.1. For lower bias voltages (about 0.2 V was usually applied) the instantaneous photocurrent was negligible owing to the fast formation of excitons. However, with some delay relative to the laser pulse a current pulse appeared. This current pulse was identified as a pile-up of current spikes originating from the break-up of EHD arriving at the negatively biased contact, acting as a reverse biased Schottky barrier diode.[8] The delay of the photocurrent onset is thus a direct measure of the time elapsed before the first EHD reach the negative contact, being dependent solely on the distance between this contact and the laser spot.

III. RESULTS AND DISCUSSION

In Fig.2 is shown the relation between x, the distance from laser spot to contact, and t, the delay time for EHD detection, at different excitation powers, revealing the expansion of the region containing EHD after a short and local excitation. The maximum range of the EHD cloud is about 0.4 mm, and is reduced by decreasing the excitation power. The major part of the EHD cloud expansion occurs within a time that is short compared with the FE life time. This part can be explained by FE diffusion in connection with a finite growth rate of EHD at rest[8] as illustrated by the dashed curve in Fig.2. This curve shows, as a function of time, the calculated linear extension of the region containing EHD with radius $R \geq 1\mu m$, assuming the EHD to be at rest. The numerical values employed in the calculations are given in the caption of Fig.2. As a "fitting" parameter is used the number N of excitons created per pulse. The curve in Fig.2 is calculated for $N \simeq 7 \times 10^{10}$ (for further details on these calculations, see ref. 8).

A more interesting result of the experiments, shown in Fig.2, is that the EHD cloud still expands slightly after several exciton life

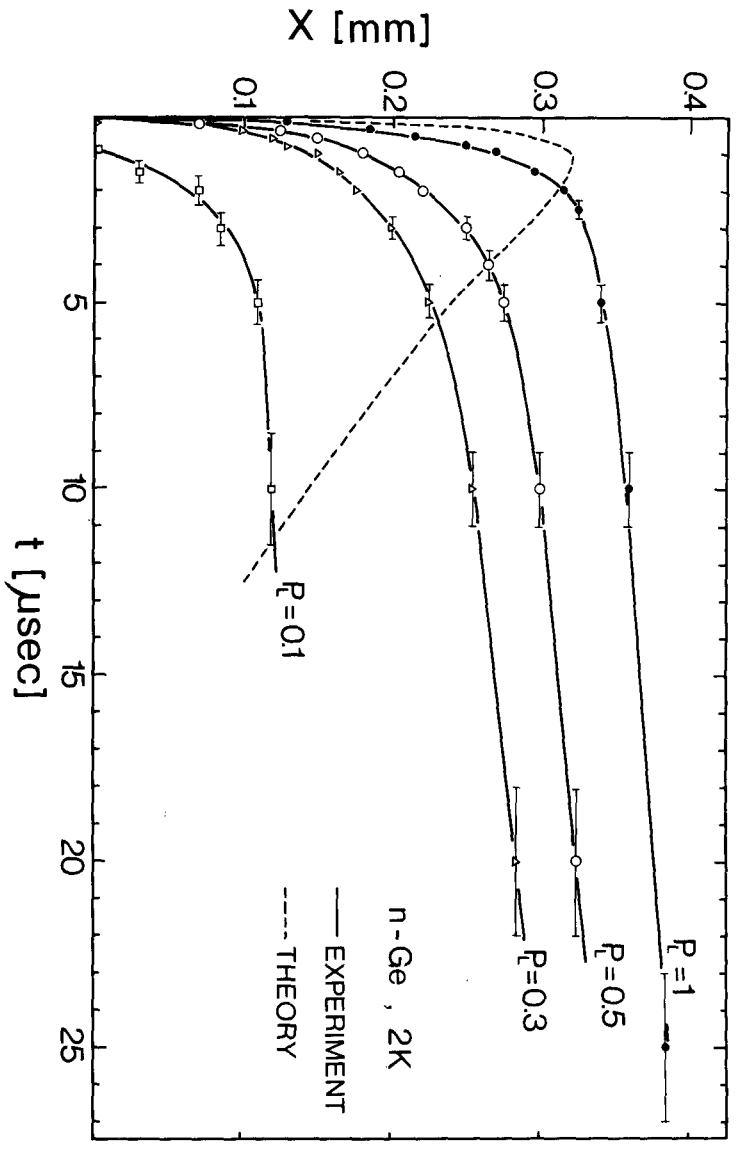

Fig.2. Expansion of EHD cloud as a function of time for different excitation powers P_L. P_L=1 corresponds to 0.5μJ/pulse. The dashed curve is a theoretical calculation based on EHD at rest (see ref. 8). The numerical values employed were: $n_c=2\times10^7 cm^{-3}$, $n_o=2\times10^{13} cm^{-3}$, $<v>=10^6 cm/s$, $D=2000\ cm^2/s$, $\tau_{ex}=5\mu sec$, where n_c is the density of the e-h plasma and n_o is the saturation value of the FE density at 2K. $<v>$, D, and τ_{ex} are thermal velocity, diffusion coefficient and life time of FE, respectively.

times. The velocity of expansion is relatively low, about 200 cm/s, and appears to be constant and independent of initial excitation power. This expansion, occurring in an environment where the FE density is far below its saturation value, is a clear evidence of real EHD motion. The expansion velocity of 200 cm/s sets the lower limit of the EHD velocities, whereas an upper limit of about 2000 cm/s can be found by comparing the actual expansion of the EHD cloud with the theory based on EHD at rest.

3.1. Motion of EHD in a Low FE Density

The observed drop velocities in the range from 200 cm/s to 2000 cm/s exceed the thermal velocity $\langle v \rangle_{EHD}$ = 100 cm/s of typical EHD with R = 5μm, eliminating an explanation in terms of drop diffusion. Moreover, the experimental curves of Fig.2 indicate a straight-line motion of the drops during their evaporation in the vacuum, implying a collision time τ_c of EHD exceeding their total life time. Hence, we can estimate $\tau_c > 25\mu$sec, suggesting that the usual scattering from phonons and impurities is effectively screened by the highly degenerate electron-hole plasma within the drops. If a collision-free motion of EHD is accepted it is obviously meaningless to introduce diffusion coefficient and drift mobility of the drops in the way it is usually done, and furthermore it has some interesting consequences in the interpretation of our experiment.

It has previously been suggested that EHD possess a net charge owing to a difference in the work-function for electrons and holes.[9,10] In the presence of an electric field a net charge on the EHD will cause an acceleration of the drops. In a time t (without collisions) an EHD with a net charge $z \times e$ (e being the elementary charge) and mass M will obtain a velocity of $V_d = \frac{z \times e \times E}{M} \times t$, where E is the bulk electric field. With E=1V/cm and t = 25μsec we find $V_d = 380 \times z$ cm/s for a drop containing 10^8 e-h pairs (R=5μm). A net charge should thus be revealed in our experiment with a resolution of the order of a single elementary charge.

However, the EHD motion experimentally observed was unaffected by an increase of the electric field up to values causing dissociation of EHD an FE in the bulk. The latter was observed as a decrease in the delayed photocurrent simultaneous with the appearance of an instantaneous photocurrent. We are therefore led to conclude that the EHD in our experiment are essentially uncharged, or at least that a possible net charge is screened effectively within a small distance from the drop surface.

3.2 Influence of FE Gas

It should be pointed out that the experiment and the above considerations refer to a situation with EHD moving in an ambient of negligible FE density ("vacuum"). In regions, where the FE density n is appreciable, the drops no longer move freely, but are influenced by the surrounding FE gas in two major respects.[7)]

1. An FE gas, of density n, exerts a friction on the EHD motion implying a velocity relaxation time $\tau_v = 2Rn_c/3n\langle v\rangle$, where the symbols have the same meaning as in Fig.2. For a drop with R=5μm moving in an FE density near saturation, $n \simeq n_o \simeq 2\times 10^{13}$ cm^{-3}, we find $\tau_v \simeq 3\mu$sec. In this case a diffusion coefficient can be defined $D_{EHD} \simeq \tau_v kT/M \simeq 0.01$ cm^2/s. It is, however, negligible small owing to the gross drop mass.

2. If the FE density is not uniform but exhibits an appreciable gradient, which is usually the case in the vicinity of a local surface excitation, the condensing excitons provide the EHD with a net momentum in the direction of decreasing FE density, tending to eject the EHD out of the highly excited region. In steady state this force is balanced by the above friction yielding a drop velocity $\bar{V}_d = -\frac{1}{9} R\langle v\rangle \cdot (\nabla n/n)$. Under typical conditions ($\nabla n/n$=10 cm^{-1}, R=5 μm) the steady state drop velocity is V_d=500 cm/s and is reached within a few microseconds.

In the present experiment steady state is never reached. Still, with the intense pulsed excitation applied, the EHD are formed in a strong FE density gradient and are thus accelerated during their growth.

Furthermore, when this driving force diminishes (after about a microsecond) so does the friction from the FE gas, leaving the EHD moving with constant velocity during their entire evaporation. Hence, this model explains qualitatively the observed EHD motion, and quantitatively it predicts velocities of the right order of magnitude.

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