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OBSERVATION OF MICROWAVE RADIATION ABSORPTION BY ELECTRON-HOLE DROPS IN Ge AND Si

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Submitted 14 February 1972
ZhETF Pis. Red. 15, No. 7, 371 - 374 (5 April 1972)

At low temperatures, the non-equilibrium electrons and holes in semiconductors are bound into excitons, and the fraction of the excitons increases with increasing pair concentration and with decreasing temperature. At a certain exciton density $n_{cr}(T)$ and at sufficiently low temperatures, the excitons can coalesce into drops and become metallized [1, 2].

The creation of metallic drops from excitons should be accompanied by a number of effects due to the formation of high-conductivity regions in the sample.

To study the formation of electron-hole drops in semiconductors, we have investigated the absorption of microwave radiation in the 8-mm band in Ge and Si samples[1]. Samples 20 - 100 mm thick were placed in a waveguide perpendicular to its broad wall, at the maximum of the electric field of the wave, and exposed to a laser pulse of 5×10^{-8} sec duration through an opening in the narrow wall. The measurements were performed in a wide temperature interval, 2.2 - 300°K. The resistance of the Ge and Si samples at 300°K was 40 and 100 ohm-cm, respectively. We registered the changes of the amplitudes of the transmitted and reflected microwave signals, due to the action of the laser light on the crystal.

Figure 1 shows oscillograms of the transmitted microwave signal for Ge samples at 2.2°K. At low pump levels, the attenuation pulse duplicates the shape of the exciting-light pulse. In this case the free carriers exist only during the time of action of the light pulse, after which they are rapidly bound into excitons, and there is no absorption of the microwave radiation.

At a laser light intensity exceeding $\sim 10^{22}$ kV/cm^{2}sec, a number of irregular sharp spikes of attenuation is produced after the termination of the light pulse. The number, durations, and amplitudes of these pulses fluctuate greatly.

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[1] Direct-current investigations of the photoconductivity do not make it possible to trace the drop-formation process, since the conductivity is then registered only after the drops have already filled the entire samples, at which instant the jump of photocurrent is observed [3, 4]. The study of IR absorption ($\hbar\omega > E_x$, where E_x is the energy of binding into an exciton) does not make it possible to distinguish between electron-hole pairs and excitons, since the IR absorption cross sections are the same in the two cases [5].

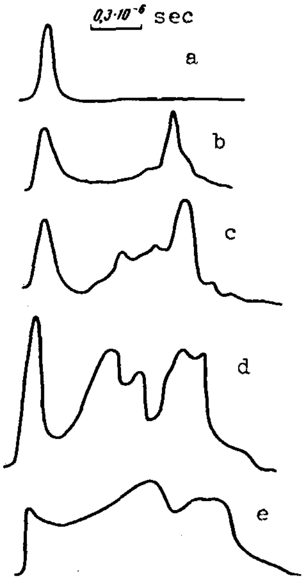

Fig. 1. Oscillograms of microwave pulse attenuation in a Ge sample at 2.2°K. The ordinate scale is arbitrary. The pump light intensity increases from a to e.

With increasing pump power, the attenuation increases and individual pulses coalesce to form a long pulse (Fig. 1).

At 4.2°K the picture becomes less distinct (Fig. 2a), for with increasing pump intensity the attenuation pulse acquires a slow component, against the background of which irregular bursts appear. The fraction of the slow component increases with the pumping. In Si (Fig. 2b) at 4.2°K and 2.2°K, a slow component likewise appears with increasing pumping. The picture in question takes place up to ∿8°K in Ge and up to ∿15°K in Si.

At higher temperatures, the attenuation pulses become smooth, and their amplitudes and durations increase. In this case, the majority of the pairs produced by the light do not combine to form excitons, and therefore the microwave-radiation attenuation pulse illustrates the fading of the electron-hole pairs. For the decrease of the signal at $T > 30°K$, the lifetime in the investigated samples was estimated to be ∿1 μsec.

It should be noted that the relative increase of the reflected-signal amplitude, which occurs when the sample is illuminated, was much smaller than the attenuation of the microwave signal passing through the sample. The experimentally observed attenuation of the microwave power is therefore the result of electromagnetic-wave energy absorption in the electron-hole plasma.

At $T > 15°K$ there is a uniform absorption over the entire illuminated part of the sample, and the oscillograms of the transmitted microwave signal are smooth (Fig. 3). They show how the conductivity of the electron-hole plasma in germanium varies with increasing particle density at 77°K. The increased duration and the tendency to saturation of the absorption pulse amplitude is due to the electron-hole scattering.

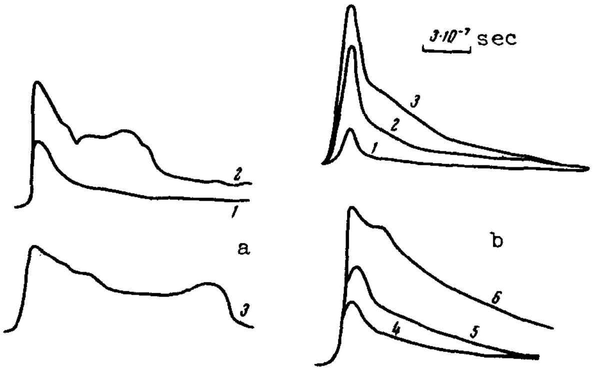

Fig. 2

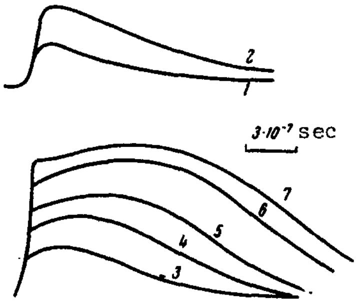

Fig. 3

Fig. 2. Oscillograms of attenuation pulses at 4.2°K: a) Ge, b) Si. The pump light intensity increases from 1 to 5.

Fig. 3. Oscillograms of attenuation pulses in the sample at 77°K. The pump light intensity increases from 1 to 7.

At lower temperatures the absorption occurring after the termination of the laser pulse occurs apparently in individual regions (drops) of the illuminated part of the crystal, since it follows from the oscillograms (Fig. 1) that the absorption has a discrete character both in amplitude and in time. Namely, the absorption of the microwave signal observed after the termination of the light pulse always exceeded 5% of the microwave power incident on the crystal. The fluctuating character of the absorption pulses, and also the presence of sharp spikes, indicates that the conductivity of the drops appears and vanishes jumpwise. These drops move randomly through the crystal, screen one another, and coalesce into larger drops[2)].

The very presence of absorption in the drop and the comparison of the absorption with that occurring in an electron-hole plasma at high temperatures apparently indicate that $\omega\tau < 1$ in the drops. At $\omega = 2 \times 10^{11}$ sec^{-1} this yields $\tau < 5 \times 10^{-12}$ sec, and leads to a carrier mobility in the drops $\mu \lesssim 10^4$ cm^2/sec-V. If the skin-layer thickness, which amounts to ~ 10 μ at $\sigma \sim 100$ (ohm-cm)$^{-1}$, exceeds the drop dimensions, then we can estimate under these conditions the microwave power absorbed in one drop:

$$\frac{P_{\text{abs}}}{P_{\text{inc}}} = \frac{\sigma E^2}{P_{\text{inc}}} V_{\text{d}} \approx 10^4 \sigma V_{\text{d}},$$

where V_{d} is the volume of the drop. For $\sigma \sim 100$ (ohm-cm)$^{-1}$ and $V_{\text{d}} \sim 10^{-9}$ cm^3 we obtain $P_{\text{abs}}/P_{\text{inc}} \sim 10^{-3}$. In the experiment, absorption in the drops sets in at $P_{\text{abs}}/P_{\text{inc}} \sim 5 \times 10^{-2}$. This is apparent evidence of simultaneous formation of a large number of drops, on the order of 100.

The authors thank V.E. Golant, S.M. Ryvkin, and I.D. Yaroshetskii for a useful discussion of the work, and also F. Sultanov and Yu. Amirov for help with the experiments.

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[2)] It seems to us that the process of absorption in the drops is also reflected in the slow component of the absorption pulse, which is observed in Ge and Si at low temperatures.