MICROWAVE BREAKDOWN OF EXCITONS IN GERMANIUM

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Research on excitons in semiconductors has aroused great interest of late. It is believed that excitons in germanium can combine at $T \lesssim 6°K$ into biexcitons and into liquid "drops" [1]. Excitons in germanium were investigated experimentally by the methods of luminescence [2, 3], dc photoconductivity [4], and light scattering [5]. We have investigated the electric properties of excitons in germanium at microwave frequencies.

We have observed the effect of thermal breakdown of excitons or of their possible formation in a microwave field, and studied the dependence of this effect on the temperature, on the energy of the optical pumping, on the microwave power, and on the external constant magnetic field. The results are discussed on the basis of the biexciton and the liquid-drop models.

The experiments were performed with a superheterodyne radiospectroscope ($\lambda = 3.2$ cm) [6]. Samples of pure germanium (residual-impurity concentration $\sim 5 \times 10^{12}$ cm^{-3}) measuring $1.5 \times 1.5 \times 0.5$ mm were placed in a reflecting resonator of $Q \simeq 10^3$. The receiver sensitivity corresponded to a free-carrier density 10^{10} cm^{-3} in the investigated samples, and the time resolution was ~ 0.6 µsec. The optical excitation was produced with an yttrium-aluminum garnet laser ($\lambda = 1.06$ µ) in the giant-pulse regime with a repetition frequency 200 Hz and a maximum energy 10^{-4} J/pulse, corresponding to a maximum generated electron-hole pair concentration $\sim 10^{18}$ cm^{-3}. The radiation was incident on the sample through a quartz light pipe, or else directly through the window of an optical cryostat. The sample was glued to a thin quartz rod and could be located at different points in the resonator, which was in turn immersed in liquid helium. The sample orientation relative to the electric and magnetic microwave fields could also be varied.

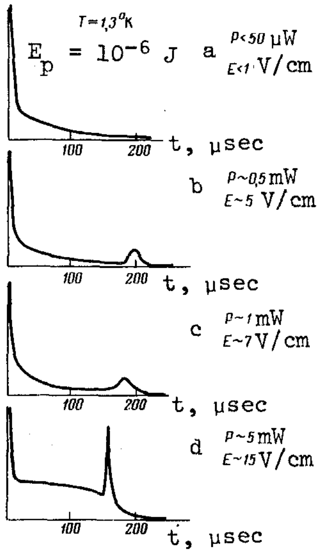

Fig. 1. Signals obtained at different microwave power levels when the sample is placed in the antinode of the microwave electric field at T = 1.3°K.

The signal of the power reflected from the microwave cavity was displayed on an oscilloscope screen. Whenever the sample was placed in the antinode of the microwave electric field in the resonator, the signal was determined mainly by resonant detuning, i.e., by the change $\Delta\varepsilon'$ of the real part of the dielectric constant. To the contrary, when the sample was placed in the antinode of the microwave magnetic field, an absorption signal was observed, of amplitude smaller by a factor 100 than in the first case. Figure 1 shows the waveforms of the signals obtained at different microwave power levels fed to the resonator, for the case when the electric field was parallel to the plane of the sample, $T = 1.3°K$ and $N_{e-h} \sim 10^{16}$ cm^{-3}. The start of the time sweep corresponds to the end of the exciting laser pulse. At low microwave levels (Fig. 1a), the signal is the sum of two exponentials with characteristic times 2 - 3 and 50 µsec, respectively. At a microwave power $P_{micr} \gtrsim 0.5$ mW, a "hump" is observed at the end of the long exponential (Figs. 1b and 1c), which moves towards the start of the sweep with increasing power, and at $P_{micr} \gtrsim 5$ mW there is observed a short spike with a rise time ∿0.6 μsec and a fall-off time 2 - 3 μsec (Fig. 1d). Figure 2 shows an oscillogram of the signal corresponding to the last case. We attribute the observed spike to a destruction (breakdown) of the excitons.[1] Detailed investigations of this breakdown effect have shown that it is observed at an optical pumping energy 10^{-7} - 10^{-6} J/pulse (non-equilibrium carrier density $N_{e-h} \sim 10^{15} - 10^{16}$ cm^{-3}) in the temperature interval 1.3 - 2.5°K. The delay time of the breakdown spike depends on the optical-excitation level, and the smaller the excitation the earlier the breakdown. We have observed a delay-time variation from 160 to 30 μsec.

The time of appearance of the breakdown spike depends on the microwave power. It appears with a delay of 160 μsec when the electric field intensity in the resonator reaches 15 V/cm ($P_{micr} \sim 5$ MW), and when the electric field intensity reaches 50 V/cm the delay time decreases to 25 μsec. The delay time decreases linearly with increasing temperature.

A constant magnetic field exerts a strong influence on the breakdown. In a field of 1 kG ($H \perp E_{micr}$), up to four breakdown spikes are observed, and the time of appearance of the breakdown first decreases with increasing H, but increases when H > 500 G. No breakdown is observed at $H \geq 2$ kG.

At low microwave levels ($P \leq 50$ μW), the argument of the long exponential becomes dependent on the level of the optical pumping (Fig. 3).

When the sample is placed in the antinode of the microwave magnetic field, the signal hardly differs in shape from Fig. 1a for all microwave-power and laser-pumping levels.

The shape of the signal at low microwave powers can be interpreted in the following manner. The short exponential apparently describes the process of binding of the free carriers excited by the laser pulse into excitons and their

Fig. 2

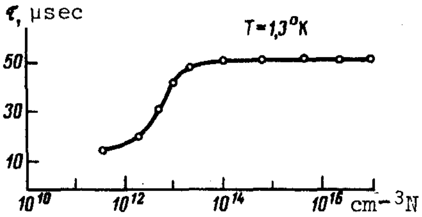

Fig. 3

Fig. 2. Oscillogram of breakdown spike, corresponding to the case d on Fig. 1.

Fig. 3. Dependence of the argument of the long exponential on the optical pumping level.

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[1] Here and below we speak, for brevity, of exciton breakdown, but mean also the disintegration of exciton formations (of biexcitons and electron-hole drops).

formations (biexcitons or drops). The long exponential (τ = 50 μsec) describes their recombination. The characteristic times of both processes coincide with the results of the investigation of the luminescence kinetics of biexcitons in germanium [3]. We note that, as follows from Fig. 3, the long exponential "goes off into the noise" at a non-equilibrium carrier density $\sim 5 \times 10^{11}$ cm^{-3} and T = 1.3°K.

When the microwave power is increased, the excitons become heated as a result of microwave-energy absorption by the residual free carriers, which transfer their energy to the excitons by collision.

At a certain critical microwave power, the excitons become strongly overheated and are destroyed (thermal breakdown).

We ascribe the presence of several breakdown spikes in the magnetic field to cyclotron resonance in the field $H \perp E_{micr}$.

Let us examine our results from the point of view of two possible forms in which excitons can exist at low temperatures.

Within the framework of the biexciton gas, the breakdown can be explained by means of the well-known theory of microwave breakdown in ordinary gases [7]. In the observed biexciton recombination processes (long exponential), their concentration decreases from the maximum value corresponding to an electron-hole pair concentration $\sim 10^{16}$ cm^{-3} (pulse energy 10^{-6} J). At a definite instant of time, the biexciton concentration goes through an optimal value $\sim 10^{14}$ cm^{-3}, when the frequency of the electron-exciton collisions coincides with the frequency of the microwave field, and a heating "hump" appears on the tail of the long exponential (Figs. 1b and 1c), corresponding to maximum absorption. At $P_{micr} \geq 5$ mW, the heating process has a cascade-like character and thermal breakdown sets in.

Let us discuss the second model, in which condensation of the excitons into a liquid phase is proposed. We assume that as a result of pulsed optical pumping there is produced a drop measuring ~10 μ. If this drop is placed in E_{micr}, then the "magnetic" absorption in it is smaller than in the field H_{micr}, and the "electric" absorption is much smaller than the "magnetic" one [8]. Thus, the thermal breakdown should be more readily observed in the field H_{micr}, in contradiction to the experimental data. The singularities of the breakdown can be qualitatively explained with the aid of the gas exciton model. If liquid drops are produced by the pulsed optical pumping, they are apparently not destroyed by the microwave field.

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ANGULAR DISTRIBUTIONS OF THE ASYMMETRY OF THE REACTION $\gamma p \to p\pi^0$ AT γ-QUANTUM ENERGIES 250, 300, AND 350 MeV

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The experimental values of the asymmetry of the cross section can supplement significantly the information needed to carry out a multipole analysis of pion photoproduction reactions, and to ensure a selection of the solutions obtained when such an analysis is carried out. At the present time, there are no experimental data on the angular distributions of the asymmetry of the reaction $\gamma + p \to p + \pi^0$.

We present here the results of measurements of the angular distribution of the asymmetry of the cross sections of the reaction $\gamma p \to p\pi^0$ at γ-quantum energies 250, 300, and 350 MeV. The measurements were performed with a beam of linearly-polarized photons [1, 2] obtained from coherent bremsstrahlung of electrons in single-crystal diamond.

The asymmetry of the cross sections was determined from the experimentally measured quantity R:

$$\Sigma \equiv \frac{\sigma_\perp - \sigma_\parallel}{\sigma_\perp + \sigma_\parallel} = \frac{1}{\bar{P}} \frac{R - 1}{R + 1}, \tag{1}$$

where $\sigma_\perp(\sigma_\parallel)$ is the cross section for the production of pions by photons having a polarization vector perpendicular (parallel) to the reaction plane, $R = C_\perp/C_\parallel$

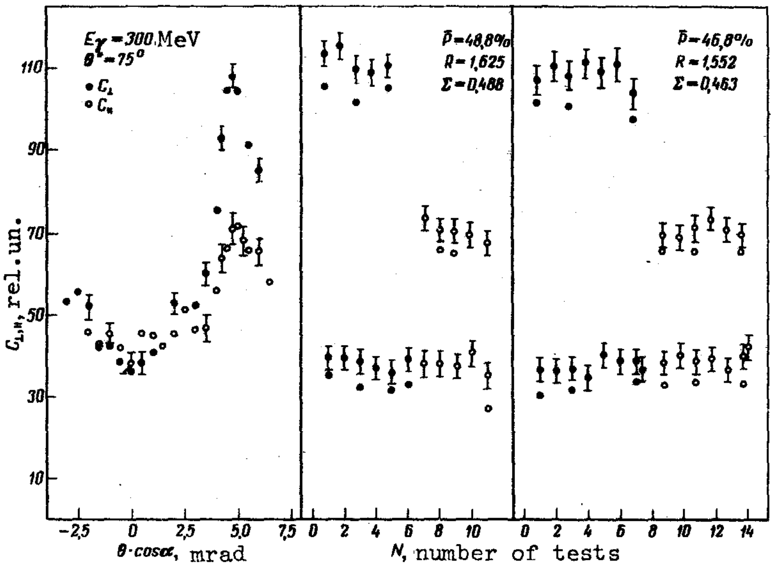

Fig. 1. Photoproton yield from the reaction $\gamma p \to p\pi^0$ vs. the angle of orientation of a single-crystal target. $\theta \sin \alpha = 75$ mrad.