CYCLOTRON RESONANCE STUDY OF DIFFUSION PROBLEMS IN HIGHLY EXCITED GERMANIUM

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ABSTRACT

Diffusion coefficients of excitons and electron-hole drops in pure germanium are measured. Use is made of 35 GHz time-resolved cyclotron resonance method. The diffusion coefficient of excitons at 4.2 K turns out to be ~1000 cm^2/s. For electron-hole drops it is lower than ~500 cm^2/s at 1.6 K.

One of the attractive topics in high excitation physics in solid will be the diffusion problem of electron-hole drops. A new method for obtaining the diffusion coefficient, not only of the electron-hole drops but of excitons in germanium, is introduced here. It takes advantage of the technique of the time-resolved cyclotron resonance at 35 GHz.

The essential part of the apparatus is given in Fig. 1. A rectangular germanium crystal, having the dimensions of $1.1 \times 1.2 \times 9.5$ mm^3, is placed through holes drilled on the broader faces of the waveguide. Excitation is made either with a xenon flash-tube in combination with a water-liquid filter, or with a Q-switched Nd: YAG laser (1.06 μm). In order to cut off undesirable excitation lights, the crystal is covered with silver paint and with tin-foil, the only exposed part being the top face. With our excitation lights, the carrier generation region is restricted within 10^{-3} cm from the surface. This thickness is much smaller than the distance between the illuminated surface and the first observation edge —— denoted x_1 in Fig. 1 —— of the inside of the waveguide, which is about 0.3 cm. A very steep gradient of the density of the photo-produced particles is expected to exist within the crystal

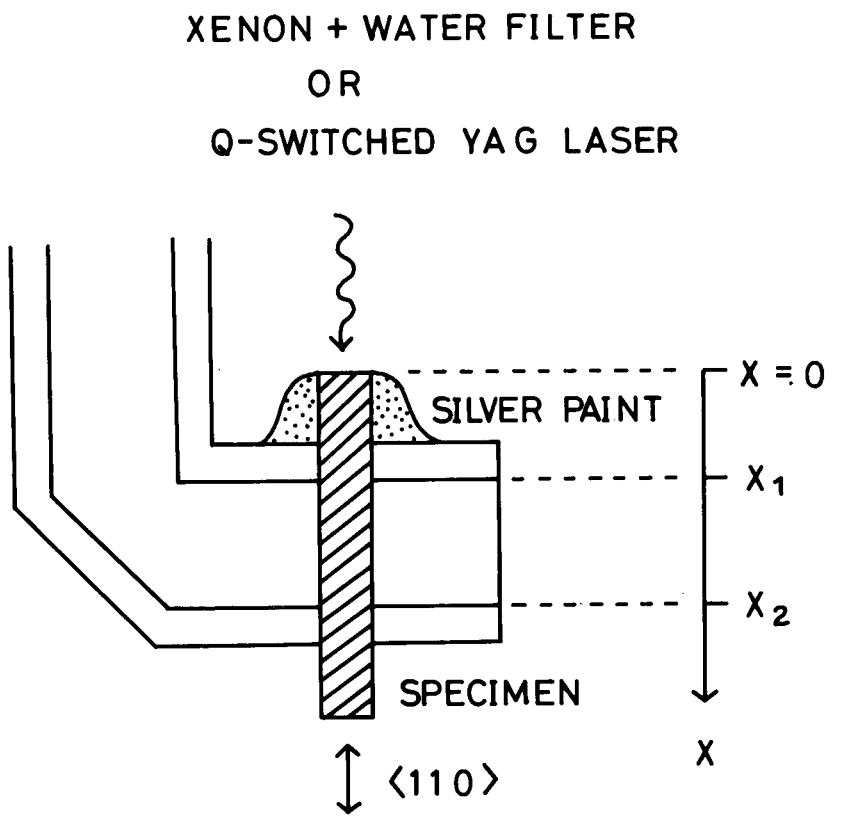

Fig.1. Scheme of the essential part of the experimental set-up.

at each excitation pulse.

With our sample shape, the problem can nearly be treated in one dimension. The diffusion equation is written as

$$\frac{\partial n(x,t)}{\partial t} = D \frac{\partial^2}{\partial x^2} n(x,t) - \frac{1}{\tau_r} n(x,t) \; ; \qquad (1)$$

where $n(x,t)$, D and τ_r are, density, diffusion coefficient and lifetime of particles, respectively. The solution of (1) is

$$n(x,t) = \frac{N_0}{\sqrt{4\pi D t}} \exp\left(-\frac{x^2}{4Dt} - \frac{t}{\tau_r}\right) \; ; \qquad (2)$$

where N_0 is the number of particles produced at $x = 0$ when $t = 0$.

Here the illuminated face is taken at x = 0. The total number of particles lying between x_1 and x_2 is given by

$$N(t) = \int_{x_1}^{x_2} n(x,t)dx. \tag{3}$$

Figure 2a shows the linewidth of electron cyclotron resonance at 4.2 K transformed to the inverse relaxation time as a function of

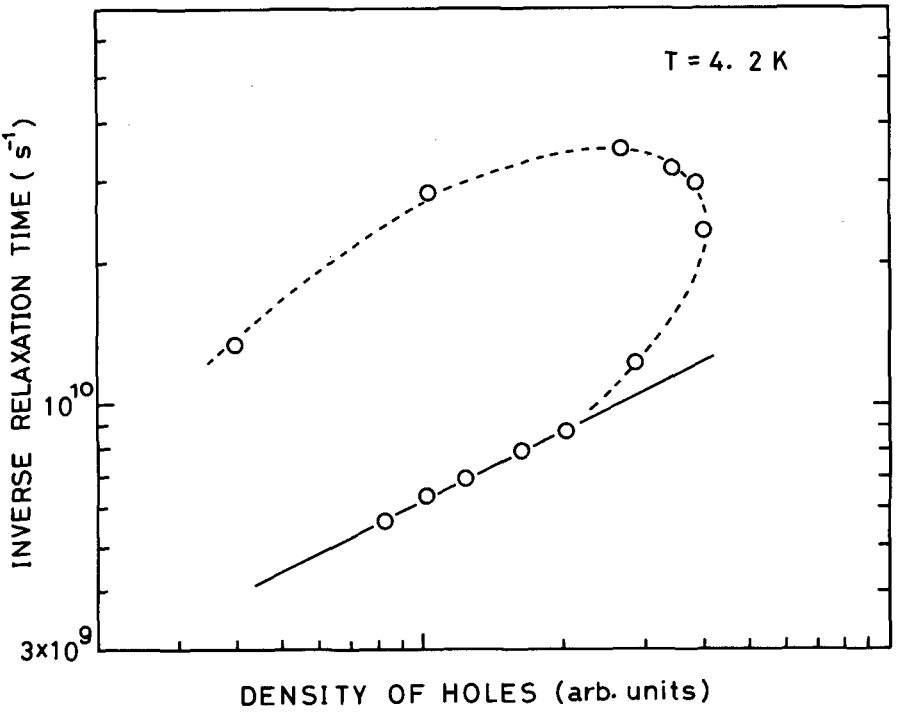

Fig.2a. Carrier density dependence of the inverse relaxation time at 4.2 K. The gradient of the solid line is 0.5, indicating the electron-hole interaction.[1)]

the relative density of holes. A xenon flash-tube was used for excitation here. The contribution of the electron-phonon interaction to the linewidth is subtracted beforehand. Circles in this figure correspond to different delay-times, though not shown explicitly. For larger delay-times, the linewidth shows proportionality to the square-root of the density of holes. This proportionality shows the electron-hole

interaction[1] to be dominant. For smaller delay-times there exists another interaction contributing to the linewidth. It is the electron-exciton interaction, which we treated before.[2] We assume the above-mentioned proportionality for the electron-hole interaction also for smaller delay-times and subtract this contribution from the linewidth. The remainder of the linewidth then yields the density of excitons. Figure 2b shows the density of excitons against the delay-time. The

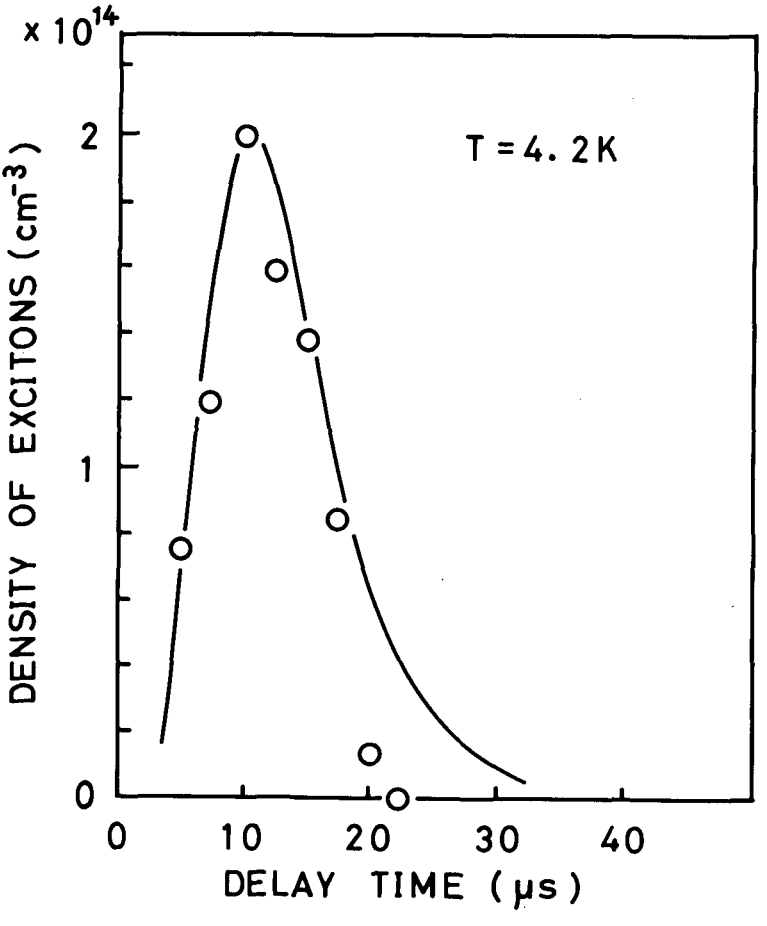

Fig.2b. Diffusion profile of the density of excitons at 4.2 K. The solid line gives the calculation with D = 1000 cm^2/s and τ_r = 4 μs.

peak value corresponds to a density of 2×10^{14} cm^{-3} when estimated from the theory by Matsuda *et al.*.[3] Fitting the peak position of the

calculated curve to that of the experimental observation, we find the diffusion coefficient of excitons to be ~ 1000 cm^2/s, using τ_r = 4 μs for excitons.*

At 1.6 K, the diffusion profile of electrons consists of two parts as shown in Fig. 3a. What is occurring inside the crystal may be as

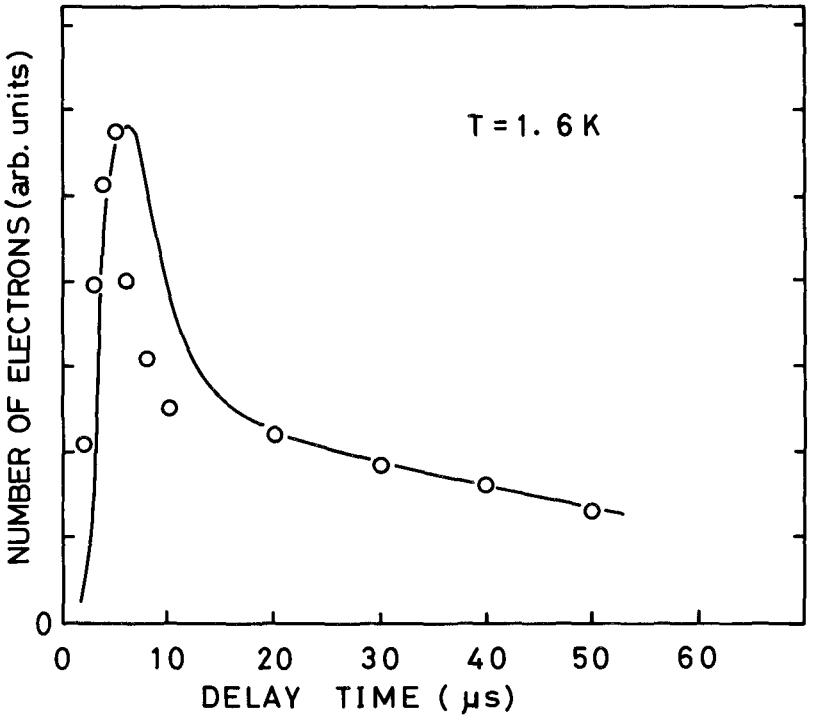

Fig.3a. Diffusion profile of electrons at 1.6 K illuminated by a xenon flash-tube.

follows. Particles created at the surface, and not associated in the drop-formation, may run inward first and will show a rapid rise-and-fall immediately after the photo-excitation. For mild excitation, drops are born only at the surface, where the density of particles is high enough to produce drops. The drops start moving and throw free particles

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* The observed value of electron lifetime at this temperature is 8 μs. It is easily shown that the lifetime of excitons is just a half of that of electrons under some appropriate conditions.[4)]

around themselves. The evaporated particles run after the primarily created ones and give rise to the slowly decaying response. If one takes this picture into account, the number of particles observed should be expressed as

$$N(t) = \exp(-t/\tau_0) \int_{x_1}^{x_2} dx \int_0^t dt' \frac{N_0}{\sqrt{4\pi D t'}}$$

$$\times \exp\left\{ \frac{-(x-\sqrt{D_0(t-t')})^2}{4Dt'} - \left(\frac{1}{\tau_r} - \frac{1}{\tau_0}\right)t' \right\} \qquad (4)$$

in place of eq.(3); where τ_0 is the decay-time of supply from drops and D_0 is the diffusion coefficient of drops. We put τ_r=2 μs, the value observed at this temperature. The quantity D for electrons is estimated to be ~ 1800 cm^2/s from the value obtained at 4.2 K. By parameter fitting the diffusion coefficient of drops is found to be less than 500 cm^2/s.

A stronger excitation is achieved with the help of a Q-switched Nd: YAG laser. When the power of microwaves is increased, sharp spikes are observed in the photoresponse signal (Fig. 3b). This feature no doubt indicates the effective bombardment on the drops by microwave-accelerated carriers. By tracing the drop-indicating photoresponse signal, or the location of the spikes, with the help of eq.(3), the diffusion coefficient of drops is found to be considerably larger than 500 cm^2/s, the upper-limiting value for the relatively low excitation case.

It seems somewhat strange that D_0 depends on the degree of excitation and that drops can have a large diffusion coefficient despite their huge masses. The high value of D_0 may be accounted for by the following reason: when excitation is very strong, the high particle density region and hence the formation of a drop will not be restricted close to the illuminated surface. In other words, the jammed-up particles produce drops while travelling inward. The observed diffusion coefficient of drops will then be hard to distinguish from that of free

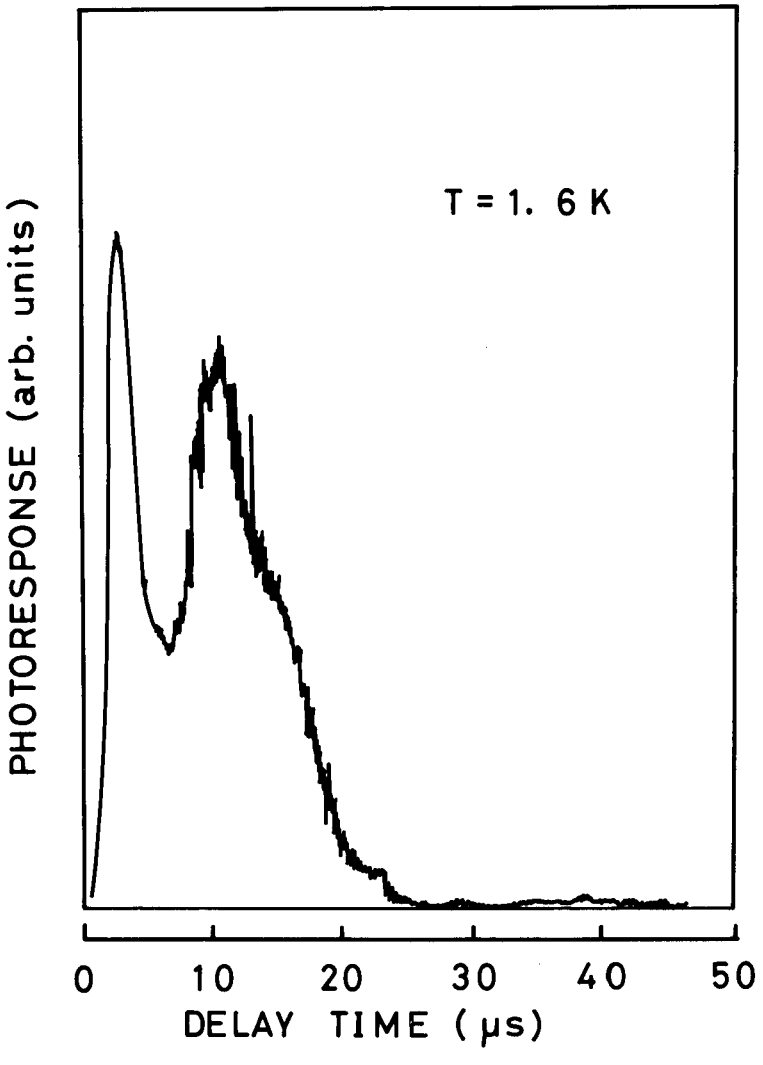

Fig.3b. Photoresponse signal with much more intense excitation lights by a Q-switched Nd-YAG laser and with a stronger power of microwaves.

particles.

It is true that too much emphasis cannot be laid on the absolute value of the diffusion coefficient for the present. But the analysis introduced here, though full of simplification, will offer some help for solving the diffusion problem in highly excited materials.

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