Magnetic-field effect on the diffusion of nonequilibrium carriers in germanium

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To investigate the magnetic-field effect on the diffusion of nonequilibrium excitons in semiconductors, the photoexcited electron-hole-exciton system in germanium has been studied, through time-resolved magneto-optical absorption measurements and space-resolved photoluminescence measurements. A striking decrease in the diffusion coefficient of excitons with increasing magnetic field is observed. It is concluded that a quasiequilibrium relation between diffusing free electrons, holes, and excitons exists, so that they have almost the same diffusion coefficient in the same magnetic field. This magnetic-field effect can be explained qualitatively by a random-walk model of electrons.

I. INTRODUCTION

Diffusion of free carriers in a semiconductor is expected to depend strongly on the magnetic field, because of the Lorentz force. There have been a few reports on the diffusion of free carriers,[1-4] mainly under zero magnetic field. Only Sanada *et al.*[3] obtained a diffusion coefficient of excitons under a weak magnetic field. No magnetic-field dependence of diffusion in a nonequilibrium carrier system has been reported so far.

The aim of this study is to obtain the diffusion coefficients of the nonequilibrium excitons under strong, weak, and zero magnetic fields, and to investigate the influence of the magnetic field. Studying diffusion of excitons will make a contribution to understand the dynamics of nonequilibrium carrier systems.

Two types of experiments have been performed to see the dependence of the diffusion coefficient on the magnetic field up to 4 T. The diffusion coefficient of carriers under strong and weak magnetic fields can be obtained by means of magneto-optical absorption measurements, employing a far-infrared (FIR) laser or microwaves, respectively. The diffusion coefficient under zero field is obtained by space-resolved photoluminescence measurement.

To get diffusion coefficients of excitons and free carriers, measurements have been performed in a special excitation arrangement, in which not only diffusion coefficients but also the lifetime of excitons and free carriers are determined.

The diffusion coefficients are found to depend strongly on the magnetic field. It is so arranged that the lifetime of excitons and free carriers can be obtained without the influence of electron-hole droplets (EHD).

Comparing the diffusion coefficient of excitons with those of electrons and holes, the existence of a quasiequilibrium relation between these three particle species is confirmed even in a diffusing system. In the microwave magneto-optical absorption measurement, although no exciton-related signals appear, the diffusion coefficient of excitons can still be deduced from the hole and electron signals. The large influence of the magnetic field on the diffusion coefficients can be explained qualitatively by means of a random-walk model. A quantitative difference between the model and our experimental result could be reduced by including an Auger recombination process in a random-walk model. A rough estimation of the effect of the Auger recombination process on the diffusion process will also be shown.

II. EXPERIMENTAL PROCEDURES

A. Magneto-optical absorption measurements

The magneto-optical absorption measurements are divided into two types; namely, microwave and FIR absorption measurements. In the former measurement, absorption peaks due to electron cyclotron resonance (ECR) and hole cyclotron resonance (HCR) can be observed under weak magnetic fields. In the latter measurement, Zeeman transition of excitons (ZEX) is also observed together with ECR and HCR signals under strong magnetic fields. The ZEX signals, however, can be observed only in the limited temperature range. To study the diffusion of excitons, not only ZEX signals but also ECR and HCR signals have been investigated under various temperatures.

High-purity germanium samples, in which the residual impurity concentrations were less than 10^{12} cm^{-3}, were employed for both experiments. Samples were always set in the Faraday configuration. All the samples had rectangular shapes, the dimension of which was typically $4\times7\times1$ mm.[3] Opposite surfaces were made unparallel with each other to avoid an interference effect. A xenon flash lamp with a pulse width of 0.5 μs was employed for excitation light, the maximum peak intensity of which was 6×10^2 J/cm^2 just before the sample.

In FIR magneto-optical absorption measurements, the transmitted signal through the sample was detected by means of a Putley-type InSb detector. The change in transmitted FIR beam intensity after intrinsic pulsed excitation was measured by means of the time-resolution technique. The time-resolved signals were detected by a boxcar integrator. The gate width of the boxcar integrator was less than 0.5 μs. Magnetic fields up to 10 T were always employed in the $\langle 111 \rangle$ direction of the samples.

The experiments were performed in the temperature range between 2.5 and 40 K. In usual magneto-optical absorption measurements, the whole area of a sample surface was illuminated by excited light to get a uniform photoexcitation. From now on, this excitation arrangement will be called "standard arrangement."[5] To determine diffusion coefficients, a special excitation arrangement is needed. This excitation arrangement is shown in Fig. 1. The origin of the x axis is set at the middle of the strip region α on the surface of the sample. The sample surface, except for region α, is covered by a black polyethylene sheet which cuts short wavelengths of the xenon light. The sample is set on a brass plate with an opening that is beneath region β. Only through this opening does the light beam come out. Even if the incident direction of the excitation light is not exactly perpendicular to the sample surface, the light beam transmitting the sample is almost perpendicular to the surface because of the large refractive index of Ge. The absorption signal through the strip region β, separated from the photoexcited strip region α by a distance d, is observed as a function of delay time after photoexcitation. The value of d is 0.8 or 1.2 mm. The width in the excitation region α is indicated by $-b$ to b and that in the region β is δd in Fig. 1. The sample thickness is given by the symbol a.

In the microwave absorption measurement, the employed wavelength was 0.856 cm (35 GHz). The magnetic field was applied up to 2 T. The sample arrangement was almost the same as that in FIR absorption measurements. The direction of diffusion, however, was made different. In microwave measurements, the direction of excitation light was parallel to that of the carrier diffusion. A water liquid filter, which cuts the wavelength longer than 1.3 μm, was employed to avoid the penetration of the excitation light into the sample. The length of the sample was 6.6 mm. A part of the sample was set inside the wave guide of microwaves. The length of this part was 2.5 mm. The remainder of the sample, outside the wave guide, was coated by silver paint to avoid exposure to the excitation light. The change in absorption by diffusing carriers in the part inside the wave guide was monitored by means of the time-resolution technique. In the survey of the excitation intensity dependence of the diffusion coefficient, neutral density (ND) filters were employed. The ND percentage numerals shown later are proportional to the intensity of the excitation light.

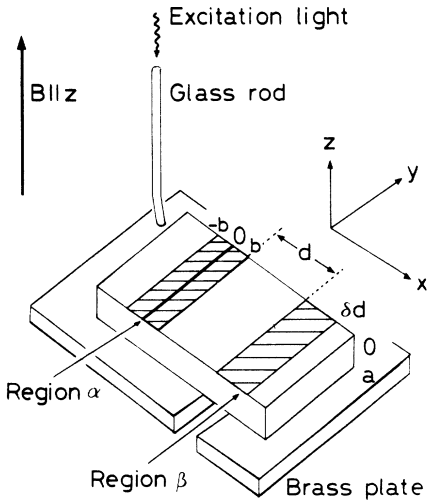

FIG. 1. Sample arrangement in a FIR magneto-optical absorption measurement for the diffusion study.

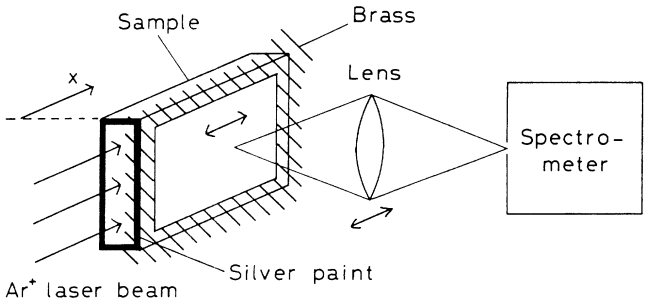

FIG. 2. Experimental setup in photoluminescence measurement. An Ar^+-laser beam is applied perpendicular to the sample surface. The x axis is set parallel to the beam, the origin of which is set on the illuminated surface.

B. Photoluminescence measurement

Figure 2 shows the experimental setup of the photoluminescence measurement to obtain space-resolved signals. The sample surface was polished after etching by CP4A (HNO_3:HF:CH_3COOH=5:3:3) to prevent the light scattering at the surface. One side of the sample was illuminated by an Ar^+ laser beam in the steady-state condition. The laser beam was focused just on the surface by a cylindrical lens. The edge of this surface was covered by silver paint. The luminescence released from the surface perpendicular to the illuminated one was observed. A brass plate was set on the plane to avoid an edge emission effect. Space-resolved signals were obtained by moving the lens along the x direction. The resultant spatially selected luminescence was guided into the spectrometer (Spex 1269) and detected by means of a Ge p-i-n detector. A lock-in amplifier was employed for phase-sensitive detection with a mechanical chopper. The spatial resolution was less than 0.3 mm.

III. DIFFUSION EQUATIONS

A. Diffusion equation in the magneto-optical absorption measurement

By the configuration in Fig. 1, nonequilibrium carriers generated within region α diffuse over the whole region of the sample. An external magnetic field is applied parallel to the z axis. The diffusing carriers have different diffusion coefficients along the directions parallel and perpendicular to the magnetic field. Because of the homogeneous excitation, no gradient in carrier density exists on the surface of region α. The term related to y from the diffusion equation can thus be dropped. The effective

masses of electrons and holes are assumed to be isotropic for transport. Only the diffusion along the x and z directions should be considered. The density of nonequilibrium carriers $n(\mathbf{r},t)$ at delay time t after pulsed photoexcitation can be expressed by the following two-dimensional diffusion equation:

$$\frac{\partial n}{\partial t}=D\frac{\partial^2 n}{\partial x^2}+D'\frac{\partial^2 n}{\partial z^2}-\frac{n}{\tau_r}\ , \tag{3.1}$$

where D and D' are diffusion coefficients for the x and z directions, respectively. The lifetime of carriers is denoted by τ_r. Carriers are generated at $t=0$ only in the strip region α by means of pulsed photoexcitation. The number of generated carriers is given by

$$N_0=\int_{\text{region }\alpha} d\mathbf{r}\, n(x,y,z,t=0)$$
$$=\Delta\int_0^a dz\, n(z,t=0)\ . \tag{3.2}$$

The excitation light illuminates the surface of region α uniformly. The density $n(x,y,z,t=0)$ is the function of z only and is independent of x and y in region α. Independence of x and y is incorporated in the constant quantity Δ.

In our experiment, the contribution of the carriers diffusing from the strip region α to the strip region β is measured by means of magneto-optical absorption. The following boundary conditions are employed to solve Eq. (3.1):

$$\frac{\partial n}{\partial z}\Big|_{z=0}=\frac{\partial n}{\partial z}\Big|_{z=a}=0\ . \tag{3.3}$$

These conditions mean that the carriers diffusing along the z direction are reflected at the surfaces ($z=0$ and a) without surface effects (for example, surface recombination). Solving Eq. (3.1) with conditions (3.2) and (3.3), integrating the solution with respect to z between 0 and a, and then integrating again with respect to x in the region $\alpha(|x|<b)$, the total number of carriers reaching region β at time t is given by

$$N(t)=\frac{N_0}{\sqrt{4\pi Dt}}\times\int_{-b}^{b}dx'\int_{b+d}^{b+d+\delta d}dx\,\exp\left[-\frac{(x'-x)^2}{4Dt}-\frac{t}{\tau_r}\right]\ . \tag{3.4}$$

This contributes to the magneto-optical absorption. Equation (3.4) is just a solution of the one-dimensional diffusion equation except for a difference in constant caused by the carrier distribution in the z direction. The experimental data of magneto-optical absorption measurements will be analyzed by means of Eq. (3.4).

In the microwave magneto-optical absorption measurement, the x axis is taken along the direction of diffusion. The photoexcitation is made at one end surface at $x=0$ that is perpendicular to the direction of carrier diffusion. The excitation light illuminates the surface uniformly. The length of the sample is denoted by x_2 (=6.6 mm). A part of the sample inside the wave guide of microwaves is from x_1 (=4.1 mm) to x_2. Neglecting the surface recombination, the one-dimensional diffusion equation should again be considered. The contribution of the total carriers in the region between x_1 and x_2 for the absorption measurement is given by

$$N(t)=\int_{x_1}^{x_2}n(x,t)\,dx$$
$$=\frac{N_0}{\sqrt{4\pi Dt}}\int_{x_1}^{x_2}\exp\left[-\frac{x^2}{4Dt}-\frac{t}{\tau_r}\right]dx\ . \tag{3.5}$$

B. Diffusion equation in the photoluminescence measurement

According to the configuration shown in Fig. 2, we consider the one-dimensional diffusion equation along the x direction:

$$\frac{\partial n}{\partial t}=D\frac{\partial^2 n}{\partial x^2}-\frac{n}{\tau_r}+G=0\ , \tag{3.6}$$

where G indicates the generation rate of carriers by photoexcitation on the surface at $x=0$. Let us simply set $G=G_0\delta(x)$, because of the short wavelength of the Ar^+ laser. The experiments are performed under steady-state excitation. Solving Eq. (3.6), the carrier density is given by

$$n(x)=\frac{1}{2}\left[\frac{\tau_r}{D}\right]^{1/2}G_0\exp\left[-\frac{x}{(D\tau_r)^{1/2}}\right]\ . \tag{3.7}$$

The luminescence intensity is proportional to the carrier density $n(x)$, then to $\exp[-x/(D\tau_r)^{1/2}]$.

IV. EXPERIMENTAL RESULTS

A. FIR absorption measurement

Figure 3 shows time variations of absorption curves at 4.2 K in the arrangement shown in Fig. 1 with $d=0.8$ mm. The FIR laser wavelength is 119 μm. An absorption peak due to ZEX is observed at 2.9 T. The numeral on the right of each curve indicates the delay time after pulsed photoexcitation. The maximum absorption intensity of ZEX is obtained at 14 μs. One should note that this delay time is quite large compared with that observed in the standard arrangement. Such a large delay is caused by the carrier diffusion from the photoexcited region α to the observed region β.

In Fig. 4, a time variation of the absorption intensity due to ZEX derived from Fig. 3 is shown. The solid and dashed lines are obtained as results of the fitting based on Eq. (3.4). From the best-fit curve (denoted by a solid line), it is found that the diffusion coefficient D and the lifetime τ_r are 50 cm^2/s and 4 μs, respectively. This diffusion coefficient is much smaller than those reported previously,[1-4] which were obtained under weak and/or zero magnetic fields. The large difference seems to indicate that the magnitude of the diffusion coefficient strongly depends on the magnetic field.

At 7.0 K, it is shown in Fig. 5 that an additional peak

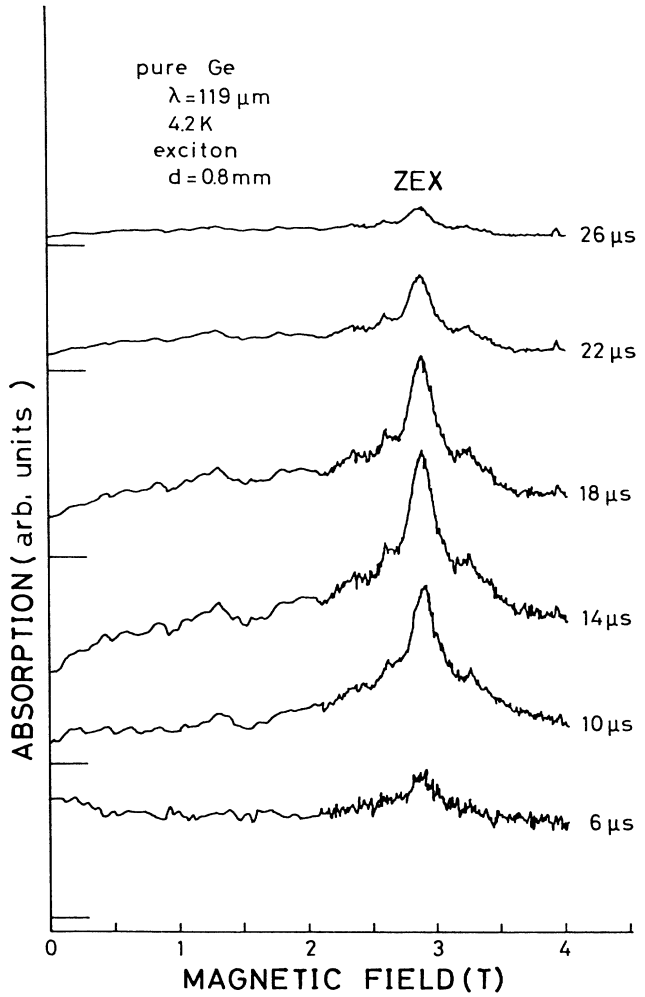

FIG. 3. A series of time resolution traces in a FIR magneto-optical absorption measurement for the arrangement shown in Fig. 1 at 4.2 K. A resonance peak due to Zeeman transition of excitons (ZEX) is observed. A large delay time is required to attain the maximum absorption intensity.

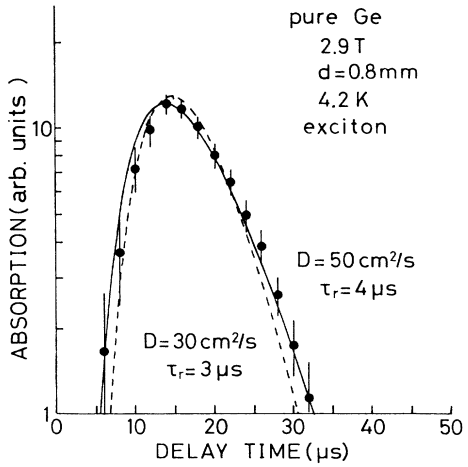

FIG. 4. Time variation of the absorption intensity due to excitons at 4.2 K derived from the ZEX peak in Fig. 3. Solid and dashed lines show the results of fitting based on Eq. (3.4). From the best-fit curve, the diffusion coefficient and lifetime of excitons are found to be 50 cm^2/s and 4 μs, respectively.

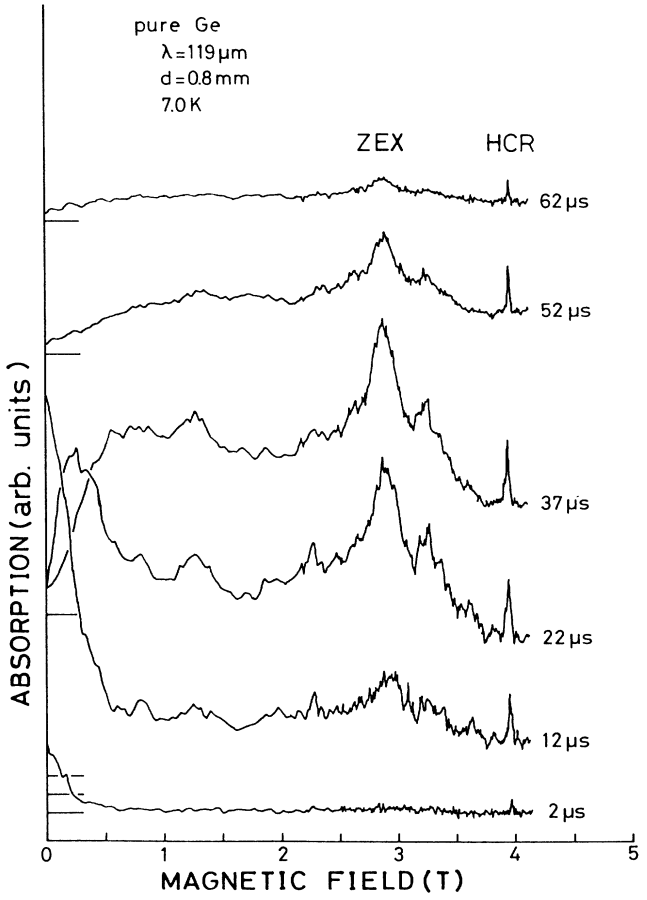

FIG. 5. A series of time resolution traces in a FIR magneto-optical absorption measurement at 7.0 K. A peak due to hole cyclotron resonance (HCR), as well as the peak due to ZEX, is observed. Both absorptions require large delay time to attain the maximum intensity.

is observed; namely, the peak due to HCR at 4.0 T. With a 220-μm laser beam, we further observe an ECR peak at 3.9 T above 6 K. At 7.0 K, large delay times are required to observe maxima of the absorption intensities of ZEX, HCR, and ECR.

B. Relation between electrons, holes, and excitons

In magneto-optical absorption or luminescence measurements, it is difficult to observe all the signals due to electrons, holes, and excitons simultaneously. At temperatures where excitons are observed, signals due to electrons and holes are weak. With an increase of temperature, excitons are dissociated into electrons and holes. The higher the temperature, the weaker the absorption intensity due to excitons. At such temperatures, where excitons are not observed, how can one observe the diffusion coefficient of excitons? If a relation in population of electrons, holes, and excitons in the diffusion condition is known, the information of diffusing excitons can be obtained from those of electrons and holes. It has been found that there exists a quasiequilibrium relation between photoexcited electrons, holes, and excitons in the

TABLE I. Fitting results of the experimental data by a one-dimensional equation, with reference to experimental conditions. The lifetimes obtained in the standard arrangement are also shown.

	T (K)	B (T)	Best fit D (cm^2/s)	Best fit τ_r (μs)	τ_r in standard arrangement (μs)
exciton	4.2	2.9	50	4	
	7.0	2.9	20	7	
electron	7.0	3.9	25	8.5	8.4
	4.2	0.1	500	3	12.4
hole	7.0	4.0	40	12	11.7

standard arrangement condition.[5]

In a very narrow temperature range near 7.0 K, coexistence of excitons, electrons, and holes can be observed in FIR absorption measurements. In Fig. 5, the time variation of the ZEX peak is shown. From the fitting of the time variation of absorption intensity due to ZEX, the diffusion coefficient of excitons is found to be 20 cm^2/s. There seems to be a slight temperature dependence in the diffusion coefficient. The peak due to HCR is also observed at 4.0 T simultaneously in Fig. 5. From the fitting of the HCR signal using Eq. (3.4), the small diffusion coefficient of holes, 40 cm^2/s, is obtained. With a 220-μm laser beam, the ECR signal is observed at 3.9 T for a temperature of 7.0 K. The diffusion coefficient is found to be 25 cm^2/s. These fitting results are tabulated in Table I. It is noted that the ECR and HCR peaks are observed almost at the same magnetic field and that electrons and holes have a quite similar diffusion coefficient. The diffusion coefficient of holes seems to be slightly larger than that of electrons. This apparent difference may be caused, in analysis, by the complexity of the valence-band structure.

If holes really had a diffusion coefficient different from that of electrons, there would arise a large space charge. To maintain charge neutrality, diffusing electrons should attract holes even if the diffusion coefficient of electrons tended to be larger than that of holes. Simple estimation indicates that such a space charge, once it occurs, relaxes immediately within the time scale of the same order of a momentum relaxation time τ of electrons. Observed electrons and holes may behave as if they had the same diffusion coefficient, since the momentum relaxation times of carriers are much smaller than the time scale of observed phenomena (several microseconds). The experimental result, in which electrons and holes have very nearly the same diffusion coefficient, can be explained by this interpretation.

Furthermore, it is noted that excitons also have practically the same diffusion coefficient as holes and electrons at 7.0 K. This result suggests the existence of a quasiequilibrium relation between excitons, electrons, and holes. From the analogy with chemical reaction, the relation may be expressed by the following form:

$$\frac{n_e n_h}{n_{\rm ex}} = \frac{n_e^2}{n_{\rm ex}} = C(T) , \tag{4.1}$$

where $n_{\rm ex}$, n_e, and n_h are the density of excitons, electrons, and holes, respectively. The quantity $C(T)$ on the right-hand side is a function of temperature of the form

$$C(T) = C_0 T^{\gamma} \exp(-\Delta E / k_B T) , \tag{4.2}$$

where

$$\gamma = \begin{cases} \frac{1}{2} & \text{for strong magnetic field} \\ \frac{3}{2} & \text{for weak magnetic field} . \end{cases}$$

The quantity ΔE is the binding energy of the exciton. We will see this quasiequilibrium relation in the temperature dependence of FIR absorption intensity due to ECR (see Fig. 10). It should be noted that, even in the diffusing carrier system under a strong magnetic field, there exists a quasiequilibrium relation as observed in the measurement in the standard arrangement.[5]

C. Microwave absorption measurements

In the microwave absorption measurements, four peaks due to ECR arising from four valleys and a peak due to HCR have been observed under weak magnetic fields. The diffusion coefficient of excitons can be deduced from the time-resolved measurement of ECR and HCR at the same strength of magnetic field, because of the quasiequilibrium relation between excitons, electrons, and holes. The absorption intensities of the ECR line at 0.1 T and the HCR line at 0.05 T are monitored. In the time variation series of ECR and HCR, the absorption intensities attain the maximum values at 17 μs of the delay time. The absorption intensities of the ECR line at 4.2 K against the delay time are plotted in Fig. 6. From a fitting of the time variation by means of Eq. (3.5), the diffusion coefficient and the lifetime of electrons are found to be 500 cm^2/s and 3 μs, respectively. This diffusion coefficient is much larger than the value at 3.9 T in FIR absorption measurements at 4.2 K.

It should be noted that the separation d can be made as large as 4.1 mm, indeed much larger than that in FIR magneto-optical measurement. That is because of the better sensitivity in microwave measurements than in FIR measurements. So an excitation intensity dependence of the diffusion coefficient can be derived. The excitation intensity dependence of the absorption decay in

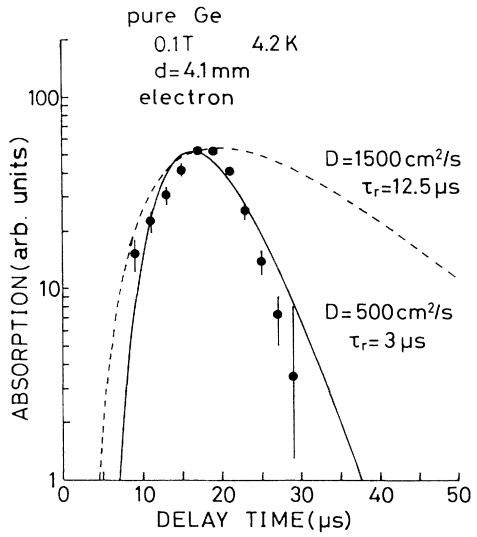

FIG. 6. Time variation of the absorption intensity due to electrons derived from the ECR line in microwave absorption measurement at 4.2 K. The solid line shows the best fit. The diffusion coefficient and lifetime of electrons are found to be 500 cm^2/s and 3 μs, respectively. The dotted line shows an unsuccessful fitting trial using the lifetime obtained in the standard arrangement.

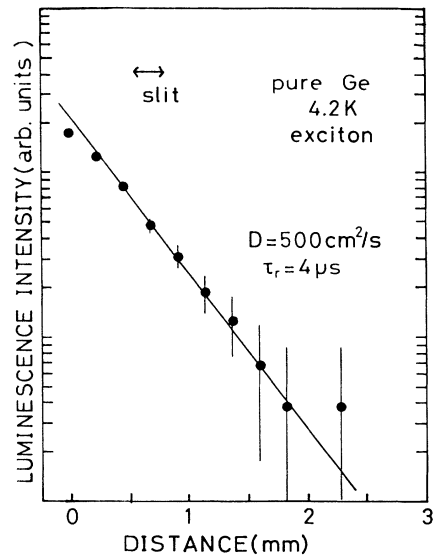

FIG. 8. A spatial dependence of the luminescence intensity due to excitons. The gradient gives a diffusion coefficient of 500 cm^2/s.

the ECR line at 2.5 K is shown in Fig. 7, in which the ND percentage numeral beside each curve indicates the relative excitation intensity. It is found that the diffusion coefficient increases with the intensity of excitation light, i.e., with carrier concentration generated by photoexcitation. With higher carrier concentration, the carrier-carrier scattering becomes more frequent. This fact suggests that the electron diffusion in the magnetic field is strongly influenced by mutual scatterings between electrons themselves.

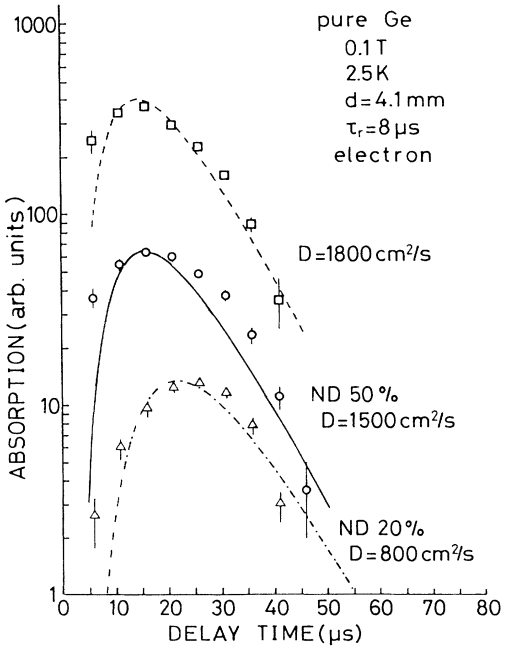

FIG. 7. Time variations of the electron absorption intensities at 2.5 K for various excitation intensities. The ND percentage numerals on the shoulder of each curve denote the relative excitation intensities.

D. Photoluminescence measurements

With the help of the arrangement shown in Fig. 2, luminescence spectra under steady-state excitation are obtained. The spectra vary with distance x between the excited region ($x=0$) and the measured region. It is noted that no peaks related to EHD have been observed, even at 4.2 K. The peaks due only to excitons have been observed. The spatial dependence of the luminescence intensity of the exciton peak with emission of longitudinal-acoustical phonons is shown in Fig. 8. The spatial variation of the luminescence intensity is an exponential decrease along the distance x as expected from Eq. (3.7). The gradient of this line gives the quantity $(D\tau_r)^{-1/2}$. The diffusion coefficient of excitons is found to be 500 cm^2/s at 4.2 K under no magnetic field, using an exciton lifetime of 4 μs, deduced from the FIR magneto-optical measurement.

E. Lifetimes and the effect of EHD

In the fitting of the time variation signals of excitons, electrons, and holes, the best fit is not obtained below 6.0 K if one uses the lifetimes observed in the standard arrangement. Figure 6 shows that the fitting trial using the lifetime 12.5 μs, obtained in the standard arrangement, is a failure (dotted line). In the best fit, the corresponding lifetime is much shorter than 12.5 μs. Below 6.0 K, the lifetimes obtained in the diffusion study are found to be smaller than those obtained in the standard arrangement. The comparison between the lifetimes obtained in the diffusion study and those in the standard arrangement is

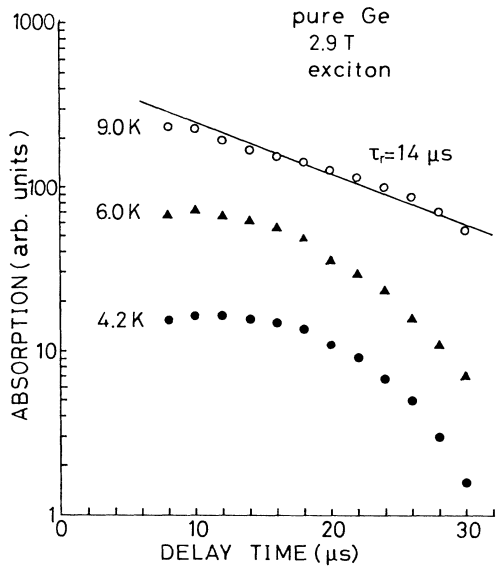

FIG. 9. Time variations of FIR absorption intensities due to excitons in the standard arrangement for various temperatures. From the gradients of these curves, the temperature dependence of the lifetime can be obtained.

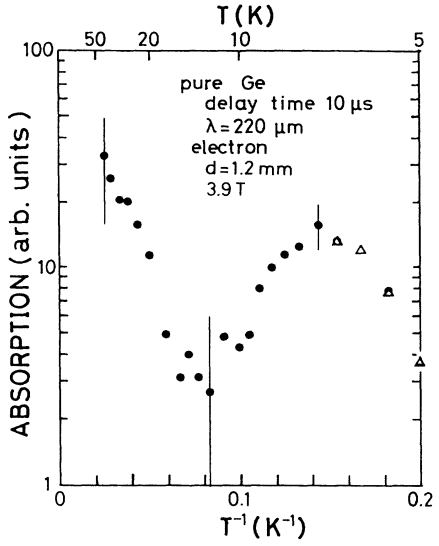

FIG. 10. Temperature dependence of the absorption intensity due to electrons at a delay time of 10 μs. The open triangles are deduced from the exciton signals, assuming the quasiequilibrium relation between electrons, holes, and excitons based on Eqs. (4.1) and (4.2).

shown in Table I.

Figure 9 shows the time variations of absorption intensity due to ZEX for several temperatures in the standard arrangement. At 9.0 K, the absorption intensity decreases with delay time exponentially. Below 6.0 K, deviation from an exponential decay due to the existence of EHD is observed. The exciton lifetime in the standard arrangement is effectively larger than expected, because of the function of EHD as a reservoir of excitons. Electrons and holes also have effectively larger lifetimes than expected.

Diffusing excitons, on the other hand, are not affected by EHD, since EHD is not moving along with excitons.[1] The difference between the lifetimes obtained in the standard arrangement and those obtained in the diffusion study arises from the existence of EHD. In the diffusion study, the true lifetimes of electrons, holes, and excitons can be observed. Above 6.0 K, EHD dissociates into excitons and carriers, and the lifetimes coincide with those obtained in the standard arrangement.

F. Temperature dependence of the diffusion

Figure 10 shows the inverse temperature dependence of the absorption intensities of ECR at 3.9 T in the diffusion study of FIR absorption measurements, in which the delay time is fixed at 10 μs. In Fig. 11, the same plot as that obtained in the standard arrangement is shown. One may note that the dip observed at 13 K in the former arrangement has not been observed in the latter, in which the absorption intensity monotonically increases with temperature. This monotonical increase is due to the dissociation of excitons into electrons and holes with the increase of temperature. The dip observed in the former arrange-

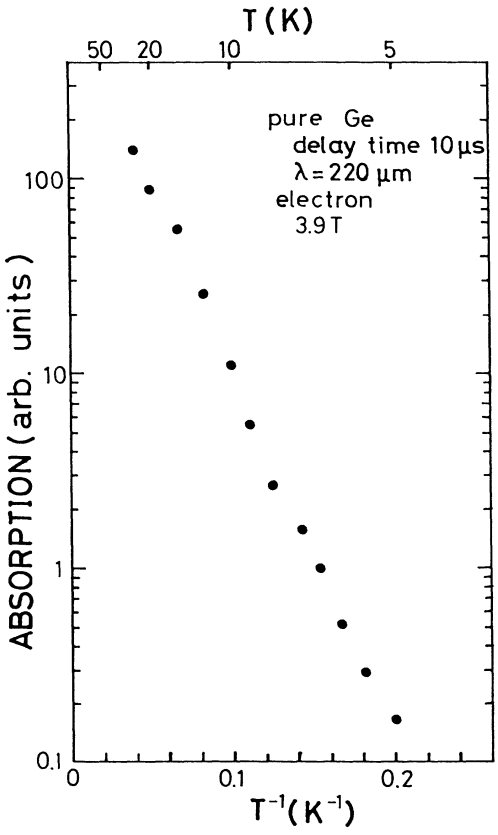

FIG. 11. Temperature dependence of the absorption intensity due to electrons at a delay time of 10 μs in the standard arrangement. No dip, as such observed in the diffusion study, is seen.

ment seems to be independent of delay time. This behavior is unexplained at present.

The open triangles in Fig. 10 are obtained from the absorption intensities of excitons, by means of Eqs. (4.1) and (4.2), based on the quasiequilibrium relation between electrons, holes, and excitons. These values (denoted by open triangles) are consistent with the temperature dependence of electronic absorption intensity (denoted by solid circles). This consistency supports the quasiequilibrium relation between electrons, holes, and excitons described in Sec. IV B.

V. DISCUSSIONS

The experimental results are tabulated in Table II. The enlisted values have been obtained by analyzing the signals from ZEX, HCR, and ECR, on the basis of the quasiequilibrium relation between excitons, electrons, and holes (mentioned in the Sec. IV B). It is seen that the diffusion coefficient decreases with magnetic field. Our result under no magnetic field seems to be consistent with that obtained by Culbertson.[4] Diffusion coefficients of excitons were also given in Refs. 2 and 3, namely 1500 and 1000 cm^2/s, respectively. Both values are larger than ours. These values were obtained in the condition that EHD coexisted with excitons. The difference in diffusion coefficients between those and ours arises from the method of estimating the lifetime. In our study, the lifetime employed has been deduced from the measurement under the condition in which the effect of EHD is eliminated.

The dependence of the diffusion coefficient on the magnetic field can be explained qualitatively by the simple one-dimensional random-walk model of electrons. The subsequent account is actually valid only for charge carriers and not for uncharged excitons. We will, nevertheless, extend our argument of random walk to excitons in view of the quasiequilibrium relation between excitons and charge carriers. In this model, electrons are scattered by phonons once in a duration τ. Electrons skip by a length l at one scattering event. The probability P with which the electron exists at the mth site after the nth event is given by

$$P=\frac{1}{2^n}\frac{n!}{\left[\frac{n+m}{2}\right]!\left[\frac{n-m}{2}\right]!} . \tag{5.1}$$

Replacing n with t/τ and m with x/l under the condition $n \gg m \gg 1$, the following expression for the probability is obtained:

$$P=\frac{1}{\sqrt{4\pi Dt}}\exp\left[-\frac{x^2}{4Dt}\right] . \tag{5.2}$$

The diffusion coefficient D is written

$$D=l^2/2\tau ,$$

where τ is the momentum relaxation time that can be deduced from the width of the ECR and HCR lines. The momentum relaxation time is estimated to be of the order of 10^{-10} s in a microwave absorption measurement[6] (weak-magnetic-field condition) and 10^{-11} s in a FIR absorption measurement[7] (strong-magnetic-field condition). The relaxation time at no magnetic-field condition is assumed to be the same as that in the weak magnetic-field condition.

Under no magnetic field, the skip length l is given by $v\tau$, where v is the thermal velocity $(k_BT/m^*)^{1/2}$. When an external magnetic field is applied perpendicular to the diffusion direction of carriers, electrons will be skipping by a cyclotron radius at one scattering event and the length l is of the order of the cyclotron radius. Under a strong magnetic field, l is assumed to be a cyclotron radius of the lowest Landau level, that is $(c\hbar/eB)^{1/2}$. Furthermore, in a weak magnetic field, electrons populate higher Landau levels. By averaging the electron distribution in the Landau levels, the quantity l is given by $(2k_BTm^*/\pi)^{1/2}(c/eB)$. The skip length l for electrons is calculated at 4.2 K for $B=0$, 0.1, and 3 T, corresponding to the zero-, weak-, and strong-magnetic-field conditions, respectively. In this calculation, the density-of-states effective mass of electrons, $0.22m^*$, is employed. Calculated values of l and D for the three cases are also listed in Table II. The simple estimation described above can explain the experimental results qualitatively. But there remains a large quantitative difference. In the above simple model, the mechanism of recombination process has not been considered. In pure germanium, there are not as many recombination centers. For a better estimation of the diffusion coefficient, one will have to take an Auger process into account.

In an Auger process, electrons are excited to higher subbands having larger cyclotron radii than those of the

TABLE II. The magnetic-field dependence of the diffusion coefficients obtained experimentally is shown with the rough estimated values calculated by the simple random-walk model. The symbols l and τ indicate the cyclotron radius and momentum relaxation time. The improved values D_A by the calculation including the Auger recombination process are also shown.

magnetic field (T)	l (Å)	τ (s)	Diffusion coefficient (cm^2/s) $D=l^2/2\tau$	D_A	(expt. D)	technique
0	17000	10^{-10}	140		500	photoluminescence (exciton)
0.1	1700	10^{-10}	1.4	350	500	microwave (ECR,HCR)
3	150	10^{-11}	0.11	6	50	FIR (ECR,HCR,ZEX)

lowest Landau subband. When electrons visiting a higher subband are scattered in the relaxation process, they skip a larger length and do so more frequently than those in the lowest subband. The scattering rate $1/\tau$ due to the deformation potential is proportional to the cyclotron radius l, so that the diffusion coefficient given in Eq. (5.3) is proportional to $(N+1)^{3/2}$, where N is the Landau quantum number. Even short stays of electrons in higher subbands, accordingly, will contribute greatly to the diffusion coefficient. We will show below an example of a rough estimation of the diffusion coefficient, considering only an Auger process as the recombination process. In the Auger process, electrons are lifted up to Landau subbands 700 meV higher than the bottom of the lowest subband (the ~400th subband). The electrons relax to the bottom of the lowest subband by successive emissions of an optical phonon, the energy of which is 37 meV, for about 18 times. The time needed for the relaxation process is estimated to be 9.6×10^{-10} s by means of the uncertainty relation. This value is much smaller than the electron lifetime (7×10^{-6} s). In the halflife ($\tau_r \ln 2$), half electrons are once excited to the higher Landau subbands due to the Auger process. In almost the entire period of the lifetime, diffusing electrons have the diffusion coefficient in the lowest subband calculated above. The enlarged diffusion coefficients by $(N+1)^{3/2}$ must be summed up for all the visiting subbands and added to the diffusion coefficient in the lowest subband, weighted by the staying time. The improved diffusion coefficient at 3 T is found to be 6 cm^2/s. From the same estimation, the diffusion coefficient at 0.1 T is found to be 350 cm^2/s. The large difference between the experimental data and the values predicted from the random-walk model has thus been reduced considerably by introducing the Auger process.

VI. SUMMARY AND CONCLUSION

Effects of magnetic field on the diffusion coefficients of nonequilibrium electrons, holes, and excitons are investigated by means of the magneto-optical absorption and photoluminescence measurements. A striking decrease in the diffusion coefficient of carriers and excitons with increasing magnetic field is observed. It is also found that, even in a diffusion process, a quasiequilibrium relation between free carriers and excitons exists, so that they have almost the same diffusion coefficient. In this study, the influence of EHD can be removed in the determination of lifetimes of electrons, holes, and excitons. The large magnetic-field dependence of diffusion coefficients can be explained qualitatively by the random-walk model of electrons including an Auger recombination process. Effects of the Auger process should thus be taken into account in transport phenomena of nonequilibrium carriers. Precise estimation of the Auger effect in the diffusion process will be considered in the future.

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