Optical saturation of the absorption coefficient of donors in Ge

H. NAVARRO*
Instituto de Física "Luis Rivera Terrazas"
Universidad Autónoma de Puebla, Apartado postal J-48, 72570 Puebla, Pue., México

R. TILL, T. THEILER AND F. KEILMANN
Max-Planck-Institut für Festkoerperforschung
7000 Stuttgart 80, Germany

Recibido el 3 de febrero de 1992; aceptado el 15 de octubre de 1992

ABSTRACT. A study of the saturation of the absorption coefficient and of the photoconductivity signal of Sb and P donors in Ge for radiation of $\lambda = 90.09$ μm, i.e. of energy very near the value of their ionization edges is presented at $T = 9.3$ K. Under these conditions negligible heating by the excess radiation energy is expected, which provides a convenient opportunity to study the kinetics of the photoionization and recombination of electrons in donor impurities. From these measurements we have determined the donor capture cross section of electrons at 9.3 K to be $\sigma_c = (1.2\pm0.7)\times10^{-12}$ cm^2 and the relaxation time from the $2s$ to the $1s$ GS as $\tau_{21} = (5.8\pm1.0)\times10^{-10}$ s. We can understand the observed saturation effects on the photoconductivity by application of the Debye-Conwell dependence of the mobility on the number of photoionized donors.

RESUMEN. Se presenta un estudio de 9.3 K de la saturación del coeficiente de absorción y de la señal de fotoconductividad de los donadores de Sb y P (antimonio y fósforo) en el germanio para radiación de $\lambda = 90.09$ μm la cual es de energía muy próxima a la del valor de sus umbrales de ionización. Bajo estas condiciones el calentamiento producido por el exceso de radiación es despreciable, lo cual proporciona una oportunidad muy conveniente para estudiar la cinética de la fotoionización y recombinación de los electrones en impurezas donadoras. De estos experimentos hemos determinado la sección eficaz de captura de electrones a 9.3 K como $\sigma_c = (1.5 \pm 0.7) \times 10^{-12}$ cm^2 y como tiempos de relajación del estado $2s$ al estado base $1s$ $\tau_{21} = (5.8\pm1.0)\times10^{-10}$ s. Podemos entender los efectos observados de la saturación de la fotoconductividad mediante la aplicación del modelo de Debye-Conwell sobre la dependencia de la mobilidad de los electrones en el número de donadores fotoionizados.

PACS: 78.50.Ge

1. INTRODUCTION

Advances in the preparation of ultrapure germanium [1] and the construction of pulsed high power far-infrared (FIR) methanol based gas lasers [2] have recently allowed precise determination of the intrinsic linewidth of donor transitions in this semiconductor and

*También en el Instituto de Investigación en Comunicación Optica, Universidad Autónoma de San Luis Potosí, Alvaro Obregón 64, San Luis Potosí, SLP 78000 (dirección a partir de febrero de 1992).

provided a probe for the physical agents that determine it [3]. In ultrapure Ge the donor complexes D(H, O) and D(Li, O) exhibit extremely narrow FIR resonances [1]. The full-width at half maximum (FWHM) of the $1s$–$2p$ D(H, O) transition, $\Delta\nu = 8.6$ μeV, was concluded to be lifetime dominated corresponding to a $T_2 = (\pi\Delta\nu)^{-1} = 1.6 \times 10^{-10}$ s (dipole relaxation time of the excited state). In a more recent work, Theiler *et al.* [4,5] have studied the power saturation broadening of the $1s$–$2p$ and $1s$–$3p$ transitions in the same D(H, O) donor of Ge concluding that the basic absorption is well described as a two level system coupled by an electric dipole moment μ with homogeneous broadening [4]. They have also conducted a series of photoconductive experiments on the D(H, O) donor ($\epsilon_i = 12.498$ meV) with radiation above but near the ionization edge, $\lambda = 90.09$ μm (111 cm^{-1}) and 90.90 (110 cm^{-1}) at high excitation powers. They observed the total bleaching of the electrons in its ground state (GS) [5].

The proper description of these phenomena in D(H, O) requires an adequate knowledge of the kinetic recombination parameters of donors in Ge. There are several studies concerning this subject in the literature [6,7,8,9], many performed in the early sixties before the advent of the high power lasers. In particular, McManus *et al.* [7] report a study of the nonlinear absorption of infrared radiation of $\lambda = 10.6$ μm, ($h\nu = 11.97$ meV) by Sb donors in Ge, i.e. for radiation more than eleven times their ionization energy. However, in these experiments in order for the electrons to come down to the bottom of the conduction band (CB) before their recapture they have to shed the excess energy by means of successive emissions of optical and acoustical phonons [10]. This process heats the distribution of electrons in the conduction band to some T_e significatively different from that of the lattice [10]. This fact affects among other physical parameters the donor capture cross section of electrons.

We present in this work a study of the saturation of the absorption coefficient and of the photoconductive signal of P $\epsilon_i = 12.88$ meV) and Sb ($\epsilon_i = 10.45$ meV) [11] donors in n-type Ge when subjected to high power pulses of near ionization edge radiation $\lambda = 90.09$ μm (111 cm^{-1}). These are model systems to study the kinetic process that governs the recapture of electrons by the D(H, O) donor center under analogous conditions, and to obtain the physical parameters that regulate the recombination of electrons promoted close to bottom of the CB. This is possible because according to the effective mass theory (EMT) the D(H, O) donor complex, as well as any other donor in Ge, have identical sets of excited states, both in their energy spacings and wavefunction nature [12], and the fact that the free electrons return through excited states to the donor GS [12].

2. EXPERIMENTAL

The Ge sample used is n-type, Sb doped, room temperature resistance $\rho = 1.15$ Ω-cm, which corresponds to $N_d = 1.5 \times 10^{15}$ cm^{-3}, of low compensation estimated to be $\beta = 2.1\%$ in the present work, Sect. 4. Its FIR transmission spectrum, taken with a Bruker 113V Fourier Transform Spectrometer shows that 80% of the donors are Sb impurities and 20% P. The sample used for the absorption saturation experiments has dimensions $10 \times 8 \times 0.35$ mm^3 while the sample used for the photoconductive experiments is $7 \times 3 \times 0.7$ mm^3. In this latter sample good low temperature ohmic contacts were prepared by rubbing

InGa eutectic vigorously on the smaller lateral faces. Both samples were wedged to avoid the formation of standing waves. Saturated absorption near the donors ionization edge was observed by measuring the transmittance of FIR pulses from a CO_2 pumped gas laser [2] operating at $\lambda = 90.09$ μm (111 cm^{-1} = 13.76 meV). These lasers are capable of producing pulses of up to 1 MW/cm^2. The pulse length is about 50 nsec. The laser power is varied in precision steps over several orders of magnitude by using a series of broadband attenuators [14]. In the absorption saturation experiments the sample is mounted in the cold finger of a liquid helium flow through cryostat. The sample temperature as measured with a Si diode next to the sample was 9.3 K. The experimental setup for the transmittance measurements is published elsewhere [15].

The photoconductive signal is measured with the voltage divider circuit shown in the insert of Fig. 2. A rectangular electrical pulse was applied at U_{in} and U_{out} was measured by means of a high speed digital oscilloscope (HP 54111D) triggering the laser after 100 μsec of waiting time. The signal was found to follow the pulse shape of the FIR laser. The load resistance R_v was adjusted according to the size of the output voltage [5].

3. Results

In Fig. 1 we plot the absorption coefficient dependence on the relative laser intensity of $\lambda = 90.09$ μm. 0 dB corresponds to a peak intensity of 25.8 KW/cm^2 and pulse energy of 0.88 mJ. The non-linear change of the absorption takes three to four decades of increasing laser intensity, with a half value for α at around -22 dB (160 W/cm^2). This behaviour is similar to that observed for the absorption at $\lambda = 10.6$ μm [7]. Accordingly, we also measure the saturation change of the average absorption coefficient $\overline{\alpha(\lambda, I)}$ resulting from the convolution of $\alpha(\lambda, I)$ with the laser pulse intensity distribution in space and time. The solid line represents the fit of a three-level model [7]. In contract to the observed results for the absorption saturation at $\lambda = 10.6$ μm, where the electrons are pumped well above the CB and substantially heated, for the results in Fig. 1, $\lambda = 90.09$ μm, the electrons are pumped just above the bottom of the CB. In this case the theoretical fit is very satisfactory, using mainly well established parameter of Ge as discussed below.

In Fig. 2 the results of the photoconductive response to the same high-power laser radiation $\lambda = 90.09$ μm are shown on the same Ge(Sb, P) sample, at applied voltages of 0.1, 0.3, 1, 3, 6 and 10 Volts. The observed changes allowed monitoring of the conductivity response up to nine decades of incident laser power. The figure shows that above a voltage of 3V, a saturation process sets in and the response to the radiation of the sample at larger fields is no longer distinguishable. This is caused by the physical limit to the temperature attainable, $T_e \approx 30$ K, by the electrons when heated by the field. This is due to the fact that at this temperature the high energy tail of the maxwellian distribution of the hot electrons has enough energy to allow emission of optical phonons, which is a highly efficient way for the electrons in Ge to dissipate their energy and saturating their drift velocity at a value $v_s = 2.2 \times 10^7$ cm/s [10].

Fig. 2 shows that for all applied voltages there is a range where a linear increase of the laser power produces a linear increase of the conductivity, but around -55 dB the slope of the response changes drastically. In the following four decades of increasing laser power the

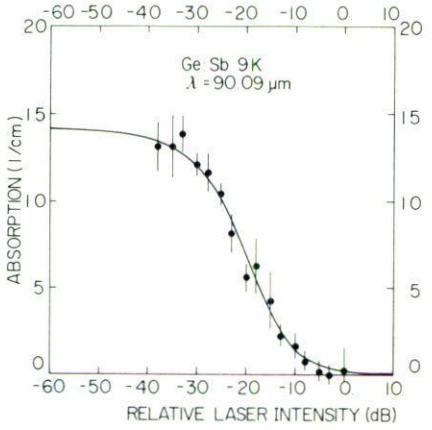

FIGURE 1. Saturation of the absorption coefficient at $\lambda = 90.09$ μm. 0 dB correspond to 25.8 kW/cm^2. The solid line shows the fit of the kinetic model illustrated in Fig. 4 and discussed in the text.

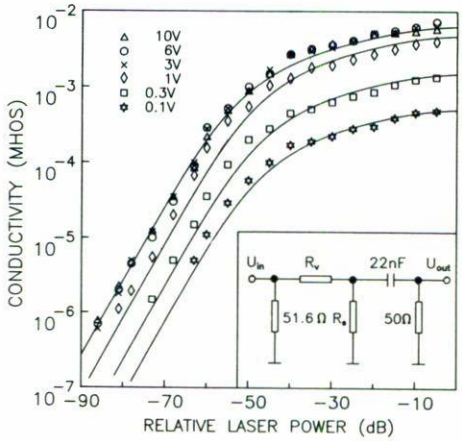

FIGURE 2. Photoconductivity response of the Ge(Sb, P) sample illuminated with laser radiation of $\lambda = 90.09$ μm. The sample is kept at $T = 9.3$ K. The insert shows the circuit used to recover the generated voltage U_{out}. The lines correspond to: (3, 6, 10 V) 1 V, (0.3, 0.1 V) from left to right, respectively.

conductivity increases by very modest increments. From the saturation behaviour of the absorption coefficient a significant depletion of the ground state population is expected optically only at incident radiation intensities 3 order of magnitude (−25 dB) larger. Hence, this change has to have its origin in the electric field dependence of either the ionization process or of the conduction of electrons in Ge. As discussed below, the solid lines represent the theoretical conductivity response due to reduction of the mobility with the increasing number of ionized donors [10].

In Fig. 3 is shown the ratio of the measured conductivities to the linear conductivities

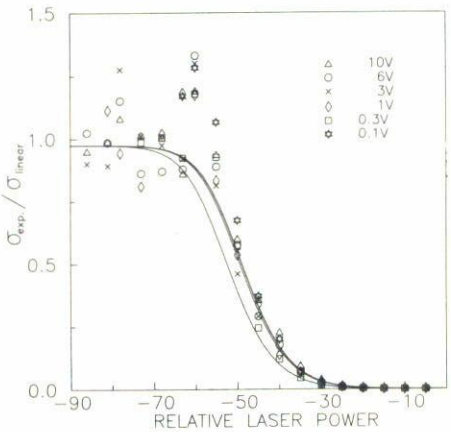

FIGURE 3. Ratio between the observed photoconductivies and those linearly extrapolated from the region of linear behaviour, *i.e.*, below −55 dB in Fig. 2. The solid lines indicate the predictions of the model discussed in the text.

obtained from a preliminarily least square linear fit to the points below −55 dB for each voltage, except for the 0.1 V values where the ratio was formed by dividing the experimental values by those of the linear approximation of the photoconductivity, Eq. (12). It can be seen from the figure that the 50% ratio lies very close to the −50 dB value. The solid lines are the predictions of the model discussed below. This predicts a weak electric field dependence for this ratio, which is not observed due to the experimental scatter. The ratios are found theoretically to be extremely sensitive to the sample compensation.

4. DISCUSSION

4.1. The saturation of the absorption coefficient

The essential process and levels involved in the kinetics of the photoionization and recombination of electrons of a donor in Ge are illustrated schematically in Fig. 4a. The recombination of an electron with a donor proceeds through its capture by some excited state and subsequent cascading by acoustic phonon emissions to the GS. The calculations of Ascarelli and Rodríguez [11] show that by large factors the most important contributions to the electron capture cross section σ_c arise from capture into the levels $2s$ and $3s$ with a subsequent transition to the GS with emission of one acoustic phonon. The capture by the state $2s$ alone contributes a factor ten times larger than that from the $3s$. Hence, in Fig. 4 only effects on the kinetics due to the capture by the $2s$ level have been depicted. Once an electron is trapped by some donor excited level in most cases it will decay to the GS, because their photoionization cross sections are several orders of magnitude smaller than that of the GS [13].

In Fig. 4, no account has been taken of the fact that donors in Ge have four possible $1s$ states originating in the fourfold degenerate CB minima chemically split into two levels, a

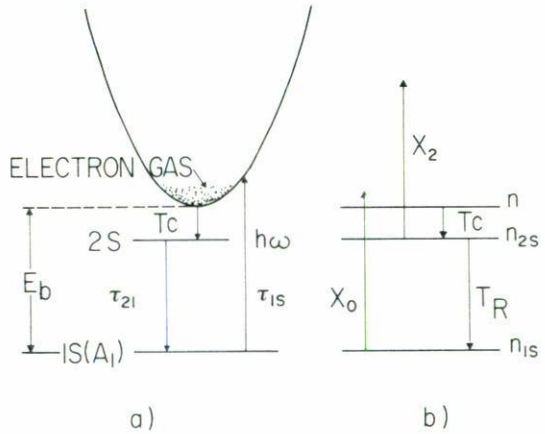

FIGURE 4. Essential kinetic process involved in the photoionization of an electron from a donor and its eventual recombination to the ground state $1s(A_1)$. E_b is the donor binding energy, T_c is the recombination rate of the free electron by the $2s$ state, τ_{21} is the lifetime of decay from this level to the GS, τ_{1s} is the photoexcitation time and $\hbar\omega$ is the laser photon energy. In b) the same process is shown schematically. Here X_0 and X_2 are the ionization rates from the GS and $2s$ states, T_R is the recombination rate from $2s$ to the GS.

singlet $1s(A_1)$ and a triplet $1s(T_2)$. The reason is that the recombination lifetime τ_{11} from $1s(T_2)$ to $1s(A_1)$ is at least one order of magnitude smaller than that of the recombination time τ_{21} from the $2s$ to $1s(T_2)$, which is the bottleneck in electron recombination, *i.e.*, less than 10^{-10} s [7,13]. The recombination lifetime τ_{32} from $3s$ to $2s$, is expected to be of the same magnitude as τ_{11} [7,13].

If the photoionization time τ_{1s} is comparable or smaller than the recombination lifetime of an excited level there can be an electron population buildup in this state. For the photoionization time $\tau_{1s} = (\sigma_{1s}\Phi)^{-1}$, where σ_{1s} is the GS photoionization cross section $\sigma_{1s} = 1.2 \times 10^{-14}$ cm^2, deduced from the FIR transmition spectrum, and Φ is the photon flux 4.54×10^{20} photons-cm^{-2}/Watt-s for $\lambda = 90.09$ μm, one finds $\tau_{1s} \approx 10^{-9}$ s at the incident power of -23 dB in Fig. 1 and above it. As a consequence, the $2s$ state will have an appreciable effect on the overall absorption process because τ_{21} has been calculated [16] to be 2×10^{-9} s, i.e., for most values of the laser power for which non-linear absorption is observed. This effect is reinforced by the fact that its photoionization cross section is at least one order of magnitude smaller [17] than that for the $1s$ electrons. Hence, the kinetics is best described by a model involving the three intervening levels: the GS, the CB, and the $2s$ state.

The power dependent $\alpha(\Phi)$ absorption coefficient expression that applies for the three level situation described above has been deduced from the corresponding rate equations in the literature [5,7] using the model illustrated in Fig. 4b with $X_0 = 1/\tau_{1s}$, $T_c = r_0(N_a + n(\Phi))$, $T_R = 1/\tau_{21}$ as follows,

$$\alpha(x) = n_{1s}(x)\sigma_{1s} + n(x)\sigma_f, \tag{1}$$

$$\alpha(x) = \alpha_0(1-\beta)R - (\alpha_0 R - \alpha) - (\beta + Rx) + \tfrac{1}{2}\left[(\beta + xR)^2 + 4xR(1-\beta)^{1/2}\right], \tag{2}$$

for compensation β, free carrier absorption cross section σ_f, and

$$x = \sigma_{1s}\frac{\Phi(1-R)}{N_d r_0}, \qquad \theta = \frac{T_R + X_2}{T_R + X_0} \tag{3}$$

and

$$r_0 = \sigma_c \langle v \rangle; \tag{4}$$

here $R \cong 0.3$ is the reflectivity of the sample, N_d is the donor concentration, r_0 is the electron recapture rate at zero electric field, composed of σ_c, the electron capture cross section, and $\langle v \rangle$, the thermal average free electron velocity, $\langle v \rangle = 4.2 \times 10^6$ cm/s at $T = 9.3$ K ($m_e^* = 0.220$). We set as an estimate of its magnitude the value for X_2 to be $X_0/10$, because in the Born approximation for the hydrogen atom $X_2 = X_0/8$ and the same order of magnitude is expected for hydrogenic impurities in Ge [13]. α_0, α are the absorption coefficients at very low and very high laser power intensities, respectively. They are defined as

$$\alpha_0 = N_d \sigma_{1s} \quad \text{and} \quad \alpha = N_d \sigma_f. \tag{5}$$

The value of $\alpha_0 = 15.2$ cm^{-1} is obtained from the FIR transmission measurement and from it $\sigma_{1s} = 1.2 \times 10^{-14}$ cm^2 at $\lambda = 90.09$ μm. Several estimates deduced mainly from conductivity measurements, dating back to the beginning of the sixties, exists for the value of the electron capture cross section σ_c [6,13]. However, there is a spread in values which puts its actual magnitude somewhere between 10^{-14} to 10^{-12} cm^2 at $T = 9.3$ K. Hence, σ_c together with τ_{21} are the least well-known parameters in Eqs. (1)-(5). As a consequence they were used as fitting parameters. The solid line represents the best fit from Eq. (2), with $\sigma_c = (1.2 \pm 0.7) \times 10^{-12}$ cm^2 and $\tau_{21} = (5.8 \pm 1.0) \times 10^{-10}$ s. Good fits were obtained for a range of σ_c values between 0.5 to 1.9×10^{-12} cm^2, and for τ_{21} for the very restricted range of values between 5 and 7×10^{-10} s. This is the origin of the uncertainties in these parameters.

Acceptable fits can be obtained to the data for the saturation of the absorption coefficient, by using the two level model of MacManus [7]. However, in this case a smaller $\sigma_c = (2.9 \pm 1.0) \times 10^{-13}$ cm^2 is required mathematically, which has the effect of prolonging the permanence time of the electrons as free carriers in order to compensate for the sizable population of electrons that tends to build up in $2s$ level in the more realistic case. These electrons, with a smaller photoionization rate, reduce the number of those available in the GS for promotion to the CB by the incident radiation. Actually, one can calculate numerically with the parameters obtained from the three level model fit that the population of electrons in the $2s$ level n_{2s} is approximately equal to n, at -18 dB of the relative laser power, *i.e.* at around 340 W/cm^2 of incident power.

The theoretical fit of the three level model provides a very satisfactory explanation of the observed saturation of the absorption coefficient of radiation with wavelength $\lambda = 90.09$ μm, in contrasts to the case of $\lambda = 10.6$ μm for the same donor system [7]. The resulting value of σ_c at $T = 9.3$ K is felt to be a very reasonable physical result. It comes

very close in magnitude to the linear extrapolated value of 1.1×10^{-12} cm^{-2} from the experimental results for σ_c of Sb donors measured by Koenig *et al.* The result for τ_{21} of 0.58 nanosec. comes close to the above mentioned theoretical value of 2 nanosec. [16]. Finally, the close agreement between the estimated capture cross sections of Koenig *et al.* [6] and that of this work using the average thermal electron velocity at 9.3 K indicates negligible heating of the electrons promoted very close to the bottom of the CB, as it was expected.

As our measurement were not very sensitive to the magnitude of the residual absorption α, its value and hence, that of the free carrier absorption cross section σ_f, were estimated by means of a preliminary fit using the theoretical expression for the power dependent absorption coefficient of a two level [17] system with residual absorption α i.e. $\alpha(\Phi) = (\alpha_0 - \alpha)/(1 + \Phi/\Phi_s) + \alpha$. We estimate $\sigma_f \cong 10^{-16}$ cm^2. Hence, this value constitutes only an upper bound due to the relative insensitivity of our experiments to it.

4.2. The photoconductivity response

Three physical sources affect the conductivity of the Ge sample when subjected to the laser illumination and measured at a given applied electric field: 1) the onset of impact ionization as an extra agent that changes the rate of ionization of donors; 2) the recombination rate becomes also field dependent, decreasing monotonically with increasing fields; and 3) the optical ionization of a significant number of donors decreases the electron mobility.

Impact ionization of impurities in semiconductors by accelerated electrons occur when their kinetic energy is larger than the impurity binding energy. The total ionization rate κ is determined by a convolution of the impact ionization cross section with the velocity distribution of hot carriers [18,19]. Following Westervelt [19] we use the empirical formula

$$\kappa = \kappa_0 \frac{\xi^{1/2}}{(1+\xi)} \frac{1}{1 + \exp E_b(1-\xi)/k_B T_h}, \quad \xi = \frac{m v_d^2}{2E_b}, \tag{6}$$

where E_b is the donor binding energy, κ_0 is a constant, T_h and v_d are the temperature and drift velocity of the hot electrons

$$v_d = v_s \frac{2}{\pi} \tan^{-1}\left[\frac{\pi}{2}\frac{\mu E}{v_s}\right]. \tag{7}$$

Here μ is the electronic mobility and v_s is the electron saturation drift velocity that from Westervelt [19] is 2.2×10^7 cm/s. The hot electrons temperature is calculated from the formula [19]

$$T_h = T + \eta m_* \frac{v_d^2}{3k_B}, \tag{8}$$

where $\eta = 2\tau_i/\tau_e$ is twice the ratio between the electron inelastic and elastic collision lifetimes discussed below.

The constant κ_0 has been estimated for acceptors [19] as 6×10^{-6} cm^3 s^{-1} with an inverse dependence on the square root of the hole effective mass. Correcting for the electron effective mass we rounded its value to $\kappa_0 = 10^{-5}$ cm^3 s^{-1}. The fit was insensitive to its actual value within an order of magnitude. For the electric field dependent recombination coefficient, $r(E)$, we used [19]

$$r = r_0 \left[\frac{3}{2}\frac{k_B T}{U}\right]^{3/2}, \qquad U = \frac{3}{2}k_B T + \tfrac{1}{2}(\eta+1)m_* v_d^2, \tag{9}$$

where r_0 is the recombination coefficient at zero field $= 5.9\times10^{-6}$ cm^3 sec^{-1}. The recombination decreases rapidly for small fields and levels off for fields above that of breakdown, 3.5 V/cm. Breakdown is of no concern in the present set of experiments because its avalanche process occurs on a time scale $\tau > 1 - 10$ μs.

The fact that the hot electron temperature is constrained to be smaller than $T \cong 30$ K, limits κ to be at least two orders of magnitude smaller than the recombination coefficient value at the same fields. As a consequence, the phenomenon of impact ionization is not the cause of the departure from the linear behaviour of the conductivity as a function of the incident power observed for the donors in this sample, Fig. 2.

Taking advantage of the fact that the departure of linearity is around -55 dB, i.e., at laser powers far below for the population build up of the $2s$ level, the kinetic equations for the electron population were simplified to that of the two level model, to calculate the photoconductivity results in this sample. The rate equations are

$$\frac{dn}{dt} = X_0 n_{1s} - (T_c - X_I)n, \qquad n_{1s} = N_d - N_a - n, \tag{10}$$

where $X_I = \kappa n_{1s}$ and now $T_c = r(N_a + n)$. This equation has the solution

$$n = \frac{N_d}{2}\left[\frac{x-\kappa}{\kappa+r} + \beta\right] + \sqrt{\left[\frac{x-\kappa}{\kappa+r} + \beta\right]^2 + 4x\frac{1-\beta}{\kappa+r}}. \tag{11}$$

For small photoexcitation this expression is approximated by

$$n = N_d \frac{(1-\beta)n}{r\beta - \kappa(1-\beta)}, \tag{12}$$

which provides the linear values for the photoconductivity which together with those of Eq. (11) are used to calculate the theoretical ratios given by the solid lines in Fig. 3. The measured photoconductivity is then

$$\sigma = \gamma(E) n e \mu, \tag{13}$$

where μ is the mobility of the sample and $\gamma(E)$ is a constant for each field that incorporates any pertinent geometrical factor and corrections due to the field dependence of the dark conductivity.

The compensation and the mobility of the sample are not known. It is well known that the mobility of an electron in Ge is determined by elastic scattering with neutral impurities, ionized impurities and by inelastic electron-phonon collisions. These processes determine the elastic and inelastic scattering lifetimes τ_e, τ_i of Eq. (8). The contribution to the final mobility originating from collisions with the number of ionized impurities n_I is strongly dependent on the level of photoexcitation.

The electron-phonon collision contribution to the mobility is well known [19] to depend inversely on the lattice temperature as $2.4 \times 10^{-7} T^{-3/2}$ cm^2/V s. This results in a value of $\mu_{ep} \cong 7 \times 10^5$ cm^2/V s at 9.3 K. The neutral impurities contribution, μ_n, has been discussed for Cu-doped Ge [20]. The authors find the theoretical expressions available in the literature to be inadequate and use μ_n as a fitting parameter. We also did so to fit the data of Figs. 2 and 3.

The contribution to the mobility dependent on the concentration of ionized impurities is given by Debye-Conwell [10] as

$$\mu_i = \frac{BT^{3/2}}{n_I} \ln\left(1 + \frac{CT^2}{n_I^{1/3}}\right), \tag{14}$$

$$B \equiv \frac{2^2 \epsilon^{1/2} m_*}{e^3} \left(\frac{8 k_B T}{\pi m_*}\right)^{3/2}, \qquad C \equiv \frac{3 \epsilon k_B}{e^2}. \tag{15}$$

Equation (14) with the theoretical coefficients of Eq. (15) results in too high values when compared with the measurements on copper doped Ge [20]. Using their experimental data, the C value of Eq. (15) and the fact that this enters in the slow varying logarithmic expression, one finds for $BT^{3/2} = 2.5 \times 10^{19}$ 1/(cm-V s) at 9.3 K. Correcting for the electron mass, $B = 3.2 \times 10^{19}$ 1/(cm-V s). The number of ionized impurities includes: the number of ionized acceptors, the number of ionized compensating donors, the number of thermally ionized donors N_0, which depends on the compensation [21] and the number of photoionized donors $\cong N_A$, i.e., $n_I = 2N_A + N_0 + n$. The dark mobility for our sample with $\beta = 2.1\%$ results in 1.0×10^5 cm^2/V s. (at 9.3 K), a value that compares well with the mobility of a similar Cu-doped Ge (N10b of Ref. [20]), $\mu = 1.02 \times 10^5$ cm^2/V s, with $N_A = 2.2 \times 10^{15}$ cm^{-3} but $\beta = 0.8\%$.

The solid lines of Figs. 2 and 3 show the theoretical fit obtained from Eqs. (6)-(14). The only free parameter used were the compensation β and the neutral impurities mobility μ_n. The $\gamma(E)$ parameter of Eq. (13) was calculated from the high photoexcitation data at 0.1 V applied voltage, and scaled linearly for the 0.3, and 1 V data. For 3, 6 and 10 V $\gamma(E)$ deviated from the expected value. Advantage was taken of the fact that in the fitting process it was found that the predicted position of the half value for the ratio of the calculated conductivities, Eq. (11) to their linear approximation, Eq. (12) was extremely sensitive to the compensation β, to the recombination rate, which is fixed from our value of r_0 and Eq. (9), and to a lesser extent on the value of μ_n. However, the uncertainty in σ_c introduces a similar one in the value of these parameters and hence $\beta = (2.1 \pm 0.9)\%$. Table I summarizes the parameters deduced from our measurements. The fit is good for most of the observed data, with some deviations between -60 to -50 dB, as well -30

TABLE I. Parameters and results of the present work and comparison with values reported in the literature.

Parameter	This work	Previous works
Absorption Coefficient		
σ_c	$(1.2 \pm 0.7) \times 10^{-12}$cm^2	1.1×10^{-12} cm^2 [6]
τ_{12}	$(5.8 \pm 1.0) \times 10^{-10}$ s	2×10^{-9}s [13]
α_0	15.2 cm^{-1}	
α	< 0.15 cm^{-1}	
Photoconductivity		
Compensation, β	$(2.1 \pm 0.9)\%$	
μ	1.0×10^5 cm^2/V s	
μ_n	3×10^5 cm^2/V s	
κ_0	10^{-5} cm^3/s	8×10^{-6} cm^3/s [19]
τ_0	5.9×10^{-6} cm^3/s	4.6×10^{-6} cm^3/s [6]

to -20 dB of excitation power, for the three lower field values. These might result from limitations of the Debye-Conwell expression, or from the empirical expressions for the hot electrons effect on the recombination and impact ionization rates.

5. SUMMARY

We have studied the saturation of the absorption coefficient and of the photoconductivity signal of Sb and P donors in Ge for radiation of $\lambda = 90.09$ μm, i.e., of energy very near the value of their ionization edges. We have determined from these measurements the donor capture cross section of electrons to be $\sigma_c = (1.2 \pm 0.7) \times 10^{-12}$ cm^2 at a temperature of 9.3 K and the relaxation time from the $2s$ to the $1s$ GS to be $\tau_{21} = (5.8 \pm 1.0) \times 10^{-10}$ s. We can understand the observed saturation effects on the photoconductivity by application of the Debye-Conwell dependence of the mobility on the number of photoionized donors. A strong dependence on sample compensation is observed for the ratio between the observed photoconductivities and those expected from an extrapolation of their region of linear dependence on the radiation. *i.e.* for small excitation powers.

ACKNOWLEDGEMENTS

The authors would like to thank Prof. H.J. Queisser for some interesting discussions on this problem. HN wishes to acknowledge the warm hospitality of the Max Planck Institut where the experimental work was performed. We thank Falk Viczian for some computing assistance and J. Hartung for assistance with the FIR Transmission measurement of the samples.

REFERENCES

1. E.E. Haller, W.L. Hansen, and F.S. Goulding, *Adv. Physics* **30** (1981) 93. Also: E.E. Haller, in *Advances in Solid State Physics (Festkoerperprobleme)*, edited by P. Gross (Vieweg, Braunschweig), Vol. 26, (1986) pp. 203–229
2. C.T. Gross, J. Kiess, A. Mayer and F. Keilmann, *IEEE J. Quantum Electron* **23** (1987) 377.
3. H. Navarro, E.E. Haller, and F. Keilmann, *Phys. Rev.* **B 37** (1988) 10822.
4. T. Theiler, F. Keilmann, and E.E. Haller, *Third Int. Conf. on Shallow Impurities in Semiconductors*, Linkoeping, Sweden (1988).
5. T. Theiler, Ph.D. Thesis, Stuttgart Univ. FRG (1989).
6. S.H. Koenig, R.D. Brown and W. Schillinger, *Phys. Rev.* **128** (1962) 1668.
7. J.B. McManus, R. People, R.L. Aggarwal, and P.A. Wolff, *J. Appl. Phys.* **52** (1981) 4748.
8. E.M. Gershenson, G.N. Gol'tsman, and N.G. Ptitsina, *Sov. Phys. JETP* **49** (1979) 355.
9. E.M. Gershenson, G.N. Gol'tsman, A.L. Elant'ev, M.L. Kagane, V.V. Multanovskii, and N.G. Ptitsina, *Sov. Phys. Semicond.* **17** (1983) 908.
10. E.M. Conwell, *Solid State Physics*, Supplement 9, F. Seitz, D. Turnbull, and H. Eherenreich, editors. Academic Press, N.Y. (1967).
11. A.K. Ramdas, and S. Rodríguez, *Rept. Prog. Phys.* **44** (1981) 1297.
12. R.A. Faulkner, *Phys. Rev.* **184** (1969) 713.
13. G. Ascarelli and S. Rodríguez, *Phys. Rev.* **124** (1961) 1321). See also: R.A. Brown and S. Rodríguez, *Phys. Rev.* **153** (1967) 890.
14. F. Keilmann, *SPIE Far-Infrared Science and Technol.* **666** (1986) 213.
15. R. Till and F. Keilmann, *Fourth Int. Conf. Infrared Physics Zurich* (1988).
16. H.A. Bethe and E. Salpeter, *Quantum Mechanics of One and Two-Electron Atoms*, Academic Press, N.Y. (1957).
17. R.H. Pantell and H.E. Puthoff, *Fundamentals of Quantum Electronics*, John Wiley, N.Y. (1969) p. 71.
18. K. Zylberztejn, *Phys. Rev.* **127** (1962) 744.
19. R.M. Westervelt and S. Teitsworth, *J. Appl. Phys.* **57** (1985) 5457.
20. P. Norton and H. Levinstein, *Phys. Rev.* **B 6** (1972) 470.
21. J.S. Blakemore, *Semiconductor Statistics* Pergamon Press, N.Y. (1962).