Transient photoconductivity in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures

Erdmann F. Schubert and Klaus Ploog
Max-Planck-Institut für Festkörperforschung, D-7000 Stuttgart 80, Federal Republic of Germany
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A new kind of transient photoconductivity (TPC) at low temperatures (4.2 K) in addition to the persistent photoconductivity was found in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures with high-mobility two-dimensional electron gas (2D EG). A model is presented for the transient part of the 2D EG carrier concentration. The decay of the carrier concentration is analyzed in terms of tunneling-assisted electron-trap recombination, and a good agreement between measured and calculated time dependence of the carrier concentration is obtained. Comparison of theory and experiments yields valuable information on the trap responsible for the TPC effect. Our evaluation technique allows us to determine quantitatively the concentration of that specific deep trap and is, therefore, a versatile tool for the characterization of selectively doped heterojunctions and for an improved understanding of their unique physical properties.

I. INTRODUCTION

In selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures, electrons from the Si donors in $Al_xGa_{1-x}As$ are transferred to the adjacent undoped GaAs layer where they form a quasi-two-dimensional electron gas (2D EG). The spatial separation between free carriers and ionized impurities leads to significantly higher electron mobilities, particularly at low temperatures and low electric fields, than those achievable in equivalently doped bulk GaAs.[1] The strongly enhanced low-field mobilities make selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures attractive for the investigation of new fundamental physical problems, including the quantized Hall effect[2] and electron localization in a 2D EG in strong magnetic fields,[3,4] and for application as high-speed field-effect transistors.[5,6]

The electronic properties of selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures are strongly affected by their exposure to light of energy below the band gap of $Al_xGa_{1-x}As$. Both the free-electron concentration and the Hall mobility increase upon illumination, and this increase persists at low temperatures even after the light has been switched off.[7] This effect is called persistent photoconductivity (PPC) and originates from bulk properties of the constituent n-type $Al_xGa_{1-x}As$ layers. According to Lang *et al.*,[8] PPC in n-type $Al_xGa_{1-x}As$ grown by liquid-phase epitaxy is caused by a donor complex (DX) center. This deep level is assumed to be a complex, in that it involves a donor atom and some lattice-point defect. When electrons are excited optically from the DX center, the recapture process is suppressed due to lattice relaxation. The model of Lang *et al.* has recently been confirmed by Künzel *et al.*[9] for bulk n-type $Al_xGa_{1-x}As$:Si grown by molecular-beam epitaxy (MBE). The difference of the ground-state energy of this trap and the conduction-band edge, i.e., the thermal ionization energy under thermal equilibrium conditions, does not vanish even at high doping concentrations, and was determined by Hall effect to be 45 meV at $N_D=2\times10^{18}$ cm^{-3}.[10] Hence, it was assumed that the DX center is controlled by a short-range potential which is not screened out even at high free-electron concentrations. When the lattice temperature is increased to approximately 100 K, recombination takes place because electrons can surmount the capture barrier. Phenomenologically, this behavior is described by a capture cross section which increases with temperature.[11]

Recently, Fischer *et al.*[12] described a photoconductive effect of selectively doped n-type $Al_xGa_{1-x}As/GaAs$ which could not be explained by PPC. The authors observed a change of the electronic properties after switching off the illumination, and thus had to discriminate between the total light sensitivity and a persistent light sensitivity. However, the physical origin of the behavior was not clarified in this study.

We have now detected a transient photoconductivity (TPC) effect in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures at low temperatures (4.2 K) in addition to PPC. Exposure to light of energy below the band gap of $Al_xGa_{1-x}As$ leads to an increase of the electron concentration during illumination. After switching off the light, the electron concentration in the dark corresponding to the PPC effect is substantially lower than the value reached immediately before the light is switched off. The observed photoconductivity is thus partly persistent and partly transient.

This paper is organized as follows. The decay of the sheet electron concentration observed in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures after switching off the light is analyzed theoretically in Sec. II by assuming tunneling-assisted electron-trap recombination and by using the Wentzel-Kramers-Brillouin (WKB) approximation. In Secs. III and IV the experimental results are presented and compared with the calculations. We discuss the nature of the specific trap responsible for TPC, including its ground-state energy, charge, and capture cross section, and its distribution in the depletion region of $Al_xGa_{1-x}As$ adjacent to the 2D EG. In additon, we have determined the concentration of the deep trap causing

TPC by monitoring the decay of the electron concentration [transient photoconductivity spectroscopy (TPCS)].

II. THEORETICAL MODEL OF TPC IN n-type $Al_xGa_{1-x}As/GaAs$ HETEROSTRUCTURES AT LOW TEMPERATURES

The typical curve of the 2D sheet carrier concentration $n_{2D\,EG}$ observed in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures under illumination as function of time is presented in Fig. 1. The decay of the carrier concentration, which occurs after the illumination is switched off, will be analyzed theoretically in terms of tunneling-assisted recombination. This process is schematically illustrated in Fig. 2(a). The tunneling-assisted recombination will be calculated by the overlap integral of the 2D EG wave function and the wave function of the impurity. The 2D EG wave function in the space-charge region of the $Al_xGa_{1-x}As$:Si layer will be calculated by the WKB method, and the impurity wave function which is thought to be strongly localized compared to the subband envelope function is approximated by the Dirac δ function. Then, the recombination of electrons with traps in the space-charge region will be described in terms of a recombination probability. Finally, the shape of the decay will be discussed.

The amplitude of the wave function ψ in the depletion region of the $Al_xGa_{1-x}As$ layer is calculated by means of the WKB method [see Fig. 2(b) for illustration]. It is given by

$$\psi=\psi_I \exp[-\Phi(z)] , \tag{1}$$

where ψ_I is the amplitude of the wave function at the interface of the two semiconductors. $\Phi(z)$ is given by

$$\Phi(z)=\left[\frac{2m^*}{\hbar^2}\right]^{1/2}\int_0^z [qV(z)-E_0]^{1/2}dz , \tag{2}$$

where $V(z)$ is the parabolic potential due to the space-charge distribution in $Al_xGa_{1-x}As$, E_0 is the electron energy at the bottom of the lowest subband, and m^* is the effective mass of electrons.

For the triangular potential well of the 2D EG, the energy of the bottom of the lowest subband is given by[13]

$$E_0=0.47\left[\frac{q^2\hbar n_{2D\,EG}}{(m^*)^{1/2}\epsilon}\right]^{2/3} . \tag{3}$$

This energy of the lowest subband was obtained by a variational calculation, which neglects the penetration of the wave function into $Al_xGa_{1-x}As$, image-force effects, many-body corrections to the energy, and the residual doping of the GaAs layer. At low temperatures the electron energy E ranges between

$$E_0 \le E \le E_F . \tag{4}$$

If one subband is populated, the Fermi energy is given by

$$E_F-E_0=\frac{n_{2D\,EG}}{D_2}=\frac{\pi\hbar^2 n_{2D\,EG}}{m^*} , \tag{5}$$

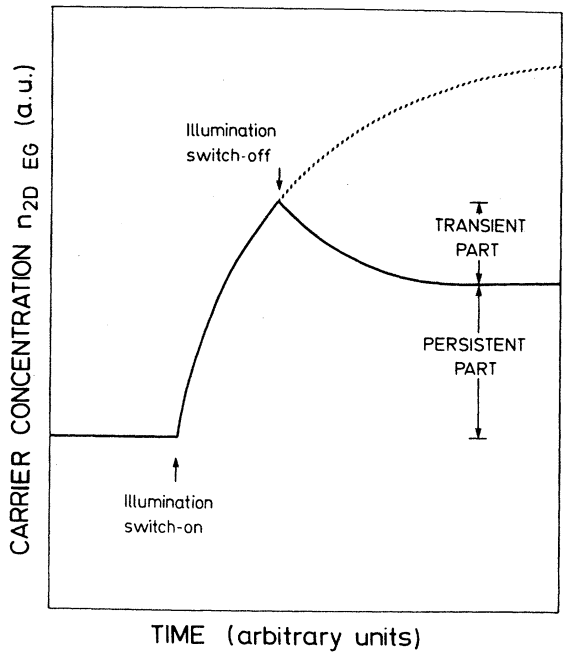

FIG. 1. Change of the 2D carrier concentration $n_{2D\,EG}$ during illumination and after the illumination is switched off. The photoconductivity consists of a transient and a persistent part.

where D_2 is the 2D density of states (twofold spin degeneracy). The energy of the conduction-band edge in depleted $Al_xGa_{1-x}As$ follows from the depletion approximation

$$qV(z)=\Delta E_c-qV_D+qV_D(W_D-z/W_D)^2 . \tag{6}$$

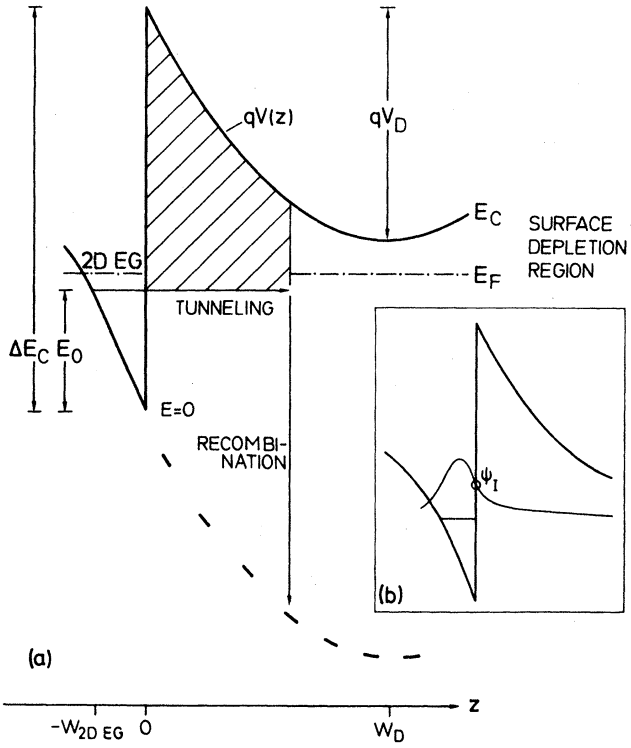

FIG. 2. Principle of the tunneling-assisted relaxation of charge carriers at deep levels in the $Al_xGa_{1-x}As$ space-charge region. Inset: decay of the 2D EG wave function in the space-charge region, which is calculated by the WKB approximation.

Here the origin of the energy is chosen to be at the semiconductor interface with E_c $(z\rightarrow 0-)=0$. The depletion width W_D is given by

$$W_D = n_{2D\,EG}/N_D \ , \tag{7}$$

assuming that all carriers are transferred across the interface. The potential drop of the conduction band V_D from $z=0$ to $z=W_D$ is

$$V_D = (qN_D/2\epsilon)W_D^2 = (q/2\epsilon)(n_{2D\,EG}^2/N_D) \ . \tag{8}$$

Since the intentional doping (shallow-donor) concentration N_D and the 2D carrier concentration $n_{2D\,EG}$ are known for each sample, the width and potential drop of the depletion region, W_D and V_D, are obtained via Eqs. (7) and (8), respectively. The combination of Eqs. (2) and (6) yields

$$\Phi(z) = \frac{(2m^*)^{1/2}}{\hbar} \int_0^z \left[qV_D \left[\frac{W_D - z}{W_D} \right]^2 - (qV_D - \Delta E_c + E_0) \right]^{1/2} dz \ . \tag{9}$$

Solving the integral results in

$$\Phi(z) = \frac{(2m^*)^{1/2}}{2\hbar} W_D \left[(\Delta E_c - E_0)^{1/2} - \frac{W_D - z}{W_D} \left[qV_D \left[\frac{W_D - z}{W_D} \right]^2 - (qV_D - \Delta E_c + E_0) \right]^{1/2} + \frac{1}{(qV_D)^{1/2}} (qV_D - \Delta E_c + E_0) \ln \left[\left\{ (qV_D)^{1/2} \frac{W_D - z}{W_D} + \left[qV_D \left[\frac{W_D - z}{W_D} \right]^2 - (qV_D - \Delta E_c + E_0) \right]^{1/2} \right\} \times [(qV_D)^{1/2} + (\Delta E_c - E_0)^{1/2}]^{-1} \right] \right] \ . \tag{10}$$

The concentration of tunneling electrons in the depletion region is

$$n(z) = n_I \exp[-2\Phi(z)] \ , \tag{11}$$

where n_I is the three-dimensional electron concentration at the $Al_xGa_{1-x}As/GaAs$ interface. It is related to the wave function by

$$n_I = n_{2D\,EG}\psi_I^2 \ . \tag{12}$$

Ando[14] calculated the amplitude of the 2D EG wave function of a selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructure by a variational method as well as self-consistently. For the normalized interface concentration, he obtained $n_I/n_{2D\,EG} = 1.4\times 10^5$ cm^{-1} (for 30 at.% Al content and $n_{2D\,EG} = 5\times 10^{11}$ cm^{-2}).

Although Ando did not note explicitly the value of the interface concentration, we obtained it graphically from his publication. Another method for obtaining the interface concentration employs the analogy of the heterojunction potential well and a square well of depth ΔE_c (see Fig. 3 for illustration). The width of the square well W_{sq} is adjusted so that the energy of the lowest subband of the square well E_{sq} and of the 2D EG, E_0 [Eq. (3)], are equal. The result of this calculation is depicted in Fig. 3 for various subband energies and the Al content as a parameter. Reasonable agreement between our calculation and Ando's value, which is included in the plot, can be verified in Fig. 3.

The recombination of electrons with traps in the $Al_xGa_{1-x}As$:Si space-charge region is described in terms of a recombination probability. The wave function of the 2D EG for $z>0$, i.e., in the $Al_xGa_{1-x}As$ layer, is obtained by the WKB method, while the wave function of the localized traps are approximated by a Dirac δ function. As a result, the recombination probability $c_n(z)$ is obtained via the overlap integral of the two wave functions

$$c_n(z) = c_o \left[\int_{-\infty}^{+\infty} \psi(z')\delta(z - z')dz' \right]^2 \ , \tag{13}$$

where c_0 is the normalized recombination probability. Solving the above integral and using Eq. (1), one obtains

$$c_n(z) = c_0\psi^2(z) = c_0\psi_I^2 \exp -2\Phi(z) \ . \tag{14}$$

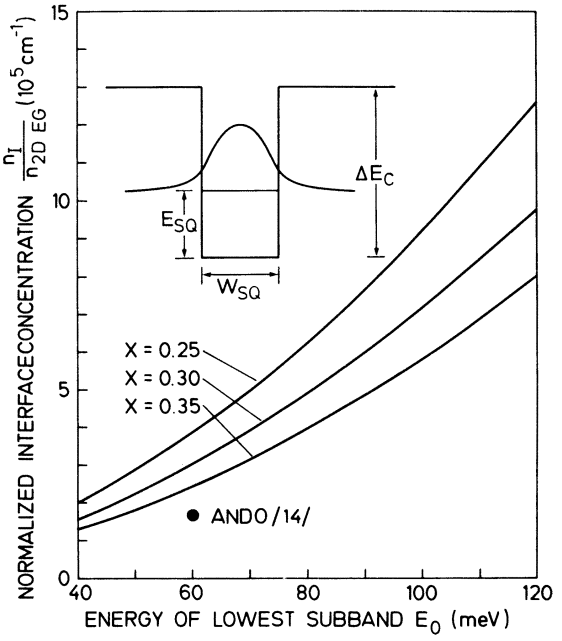

FIG. 3. Normalized interface concentration vs energy of the lowest subband. Ando's results (Ref. 14) for $E_0=60$ meV ($n_{2D\,EG}=5\times 10^{11}$ cm^{-2}) and $x=0.3$ is included.

In bulk material the capture process is usually expressed in terms of a capture cross section of the trap σ and of the electron velocity. This model, however, has to be used very carefully, since the recombination process is tunneling assisted in our case. Although this model is not fully applicable in this context, we use it to get a rough estimate of the capture cross section of the trap. Instead of Eq. (14), we write

$$c_n(z)=\sigma v_T n_{2D\,EG}\psi^2(z)\ , \tag{15}$$

where v_T is the carrier velocity in the transverse direction to the potential well. An approximation for the transverse velocity is

$$v_T=(2E_0/m^*)^{1/2}\ . \tag{16}$$

Thus the capture cross section of the trap σ can be estimated.

The mean time of an electron to be captured by a deep empty trap increases with the distance from the interface, and is given by

$$\tau(z)=1/c_n(z)\ . \tag{17}$$

Therefore, the concentration of deep empty traps is

$$N_T^0(t,z)=N_T^0(0,z)\exp[-t/\tau(z)]\ . \tag{18}$$

We assume that the trap is neutral when empty and negatively charged when occupied by an electron, i.e., it is acceptorlike. This assumption will be justified later. If all traps responsible for the TPC effect are empty (high-intensity illumination), Eq. (18) results in

$$N_T^0(t,z)=N_T\exp(-t/\tau)\ . \tag{19}$$

A homogeneous spatial distribution of the trap is thereby assumed. For the 2D concentration of neutral traps in the entire depletion region, $N_T^{0(2)}$ follows from the integration of Eq. (19),

$$N_T^{0(2)}(t)=N_T\int_0^{W_D}\exp(-t/\tau)dz\ . \tag{20}$$

By using Eq. (20) and assuming that all traps in the depletion layer are involved in the TPC effect, the free-electron concentration in the accumulation channel at the semiconductor interface, $n_{2D\,EG}$, is given by

$$n_{2D\,EG}(t)=n_{2D\,EG}(0)-N_T\left[W_D-\int_0^{W_D}\exp(-t/\tau)dz\right]\ . \tag{21}$$

Again, $\tau(z)$ is given by Eq. (17). Since an analytic solution of the integral in Eq. (21) is difficult, we used a numerical evaluation and employed Simpson's rule.

The concentration of the trap responsible for TPC, N_T, and the recombination probability of this trap, determine the decay of the 2D EG concentration $n_{2D\,EG}$ with time. A high concentration of traps results in the loss of a large number of carriers. A large recombination probability results in a fast decay. Some examples of the carrier concentration decay versus time for various capture cross sections and trap concentrations are illustrated in Figs. 4 and 5. The averaged lifetime τ_A of the electrons increases with time according to

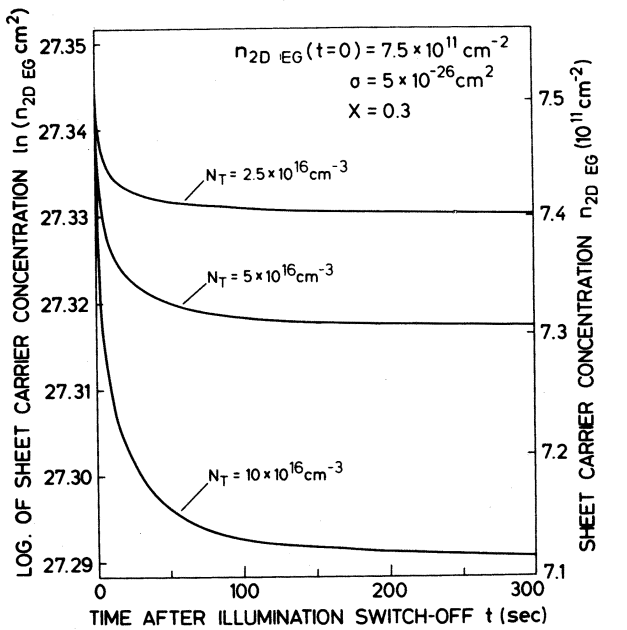

FIG. 4. Theoretical decay of the 2D carrier concentration $n_{2D\,EG}$ for various concentrations of the deep trap in $Al_xGa_{1-x}As$ responsible for the TPC effect.

$$\tau_A=-\frac{d\ln[n_{2D\,EG}(t)-n_{2D\,EG}(\infty)]}{dt}\ . \tag{22}$$

This is reasonable, since within short times after which the illumination is switched off, electrons will recombine with traps near the interface. The recombination lifetime becomes larger with increasing z, since $\psi(z)$ decreases with distance from the interface.

The tunneling-assisted relaxation should also affect the

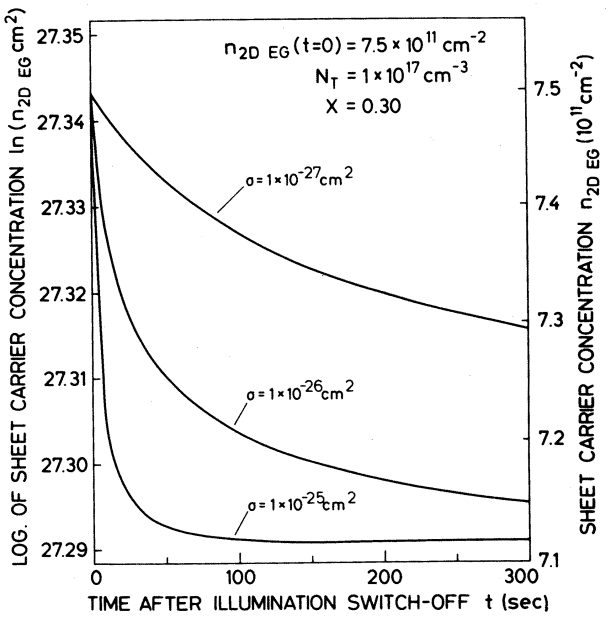

FIG. 5. Theoretical decay of the 2D carrier concentration $n_{2D\,EG}$ for various capture cross sections of the deep trap responsible for the TPC effect.

mobility of the 2D EG, because the scattering rate by remote charged centers is changed by the recombination process. If the trap is acceptorlike, the mobility should decrease during the relaxation, since the number of charged scattering centers in the depletion layer increases. The mobility change will be discussed in greater detail in Sec. IV B.

III. EXPERIMENTAL

The selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures for this study were grown by MBE on (100)-oriented semi-insulating GaAs substrates at substrate temperatures of 650—670 °C. Details of the growth procedure and of the design parameters of the heterostructures have been described elsewhere.[10] The $Al_xGa_{1-x}As$ alloy composition was chosen to be $x=0.30$, and the intentional doping concentration $N_D=2\times10^{18}$ cm^{-3} gives a sheet electron concentration of $n_{2D\,EG}=7\times10^{11}$ cm^2 at $T=77$ K which is favorable for application of these structures as high-electron-mobility transistors. These values of alloy composition and of doping concentration were also used in the calculations. For the photoconductivity measurements the samples were defined photolithographically and etched into Hall bars with two current contacts and six potential probes. The Ohmic contacts were formed by the placement of small Sn spheres (or by vacuum-evaporating planar Sn-Au contacts on the contact areas of the Hall bar), and then alloying at $T=380$ °C in a flowing-gas mixture of 80% nitrogen and 20% hydrogen for 4 min. This procedure yields specific contact resistances below 10^{-5} Ω cm^2.

During Hall-effect and conductivity measurements the sample was mounted on a Cu block and placed either in a liquid-He—bath cryostat or in a variable-temperature continuous-flow cryostat, both providing a constant temperature of 4.2 K. The current fed to the sample was chosen to be 1 μA, corresponding to an electric field of less than 1 mV/cm in order to avoid hot-electron effects. Joule-heating effects due to the dissipated power in the sample and the illumination can be excluded.

The time-dependent Hall voltage and the voltage along the bar (to determine the resistivity of the sample) were measured with a high-impedance nanovoltmeter. As an incoherent monochromatic light source for illumination of the sample we used a GaAs light-emitting diode having an emission wavelength of approximately 820 nm in order to avoid band-to-band excitation in the $Al_xGa_{1-x}As$ layer. The decay of the voltages after illumination were sampled every 5 sec. The time constant of the measuring circuit (i.e., RC time and sampling time of the digital voltmeter) were much smaller than the measuring intervals. The steady-state 4.2-K sheet electron concentration and mobility of the studied samples are given in Table I.

IV. RESULTS AND DISCUSSION

A. Carrier relaxation

When a selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterojunction is exposed to light of energy below the band gap of $Al_xGa_{1-x}As$ at low temperatures, the carrier concentration of the 2D EG increases. The rate of this increase depends on the intensity and the dose of the illumination. During illumination, electrons are excited from deep traps in $Al_xGa_{1-x}As$ (donor type or acceptor type) into the conduction band of the ternary alloy. If the excitation happens to be in the depletion region of the 2D EG ($0<z<W_D$), electrons will move to the 2D EG, since there are empty states available at lower energy. The excitation of the electrons from DX centers is persistent, as this center has a very small capture cross section at liquid-He temperature [$<10^{-31}$ cm^2 (Ref. 11)]. If the capture cross section, and thereby the recombination probability, is larger, electrons will recombine with the trap even at low temperatures. In Sec. II we showed that this behavior can be understood in terms of tunneling-assisted electron recombination. After the excitation, the selectivity doped heterostructure is in a metastable state, since there are empty states available at lower energy. A necessary condition for the relaxation process is that the trap is lower in energy than the 2D EG, that is, at least $\Delta E_c-E_0\simeq200$ meV below the conduction band of the $Al_xGa_{1-x}As$.

In Figs. 6 and 7 we have plotted the measured decay of the carrier concentration $n_{2D\,EG}$ versus time after the illumination was switched off for two representative samples. The decay for times larger than 300 sec is not significant and is therefore omitted here. For comparison, the calculated decay of the carrier concentration is also included in the plots. The two variables, namely the concentration N_T and the capture cross section (recombination probability) σ of the trap, were determined by fitting the calculated curves to the experimental data. In both samples the capture cross section of the TPC trap has approximately the same value (1.9×10^{-26} and 3.0×10^{-26} cm^2, respectively). Therefore, we conclude that one specific trap, that we will call the TPC trap, is present in all selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterojunctions investigated and is thus responsible for this TPC effect. The physical nature of the TPC trap does not change in samples of different design parameters

TABLE I. Steady-state sheet carrier concentration $n_{2D\,EG}$ and mobility μ measured at 4.2 K in selectively doped n-type $Al_{0.3}Ga_{0.7}As/GaAs$ heterostructures of the present study.

Sample no.	Dark		After light exposure	
	$n_{2D\,EG}$ (cm^{-2})	μ (cm^2/V s)	$n_{2D\,EG}$ (cm^{-2})	μ (cm^2/V s)
4222	6.6×10^{11}	15000	8.5×10^{11}	22000
5185	6.9×10^{11}	148000	9.9×10^{11}	138000
5163	2.5×10^{11}	35000	4.2×10^{11}	96000

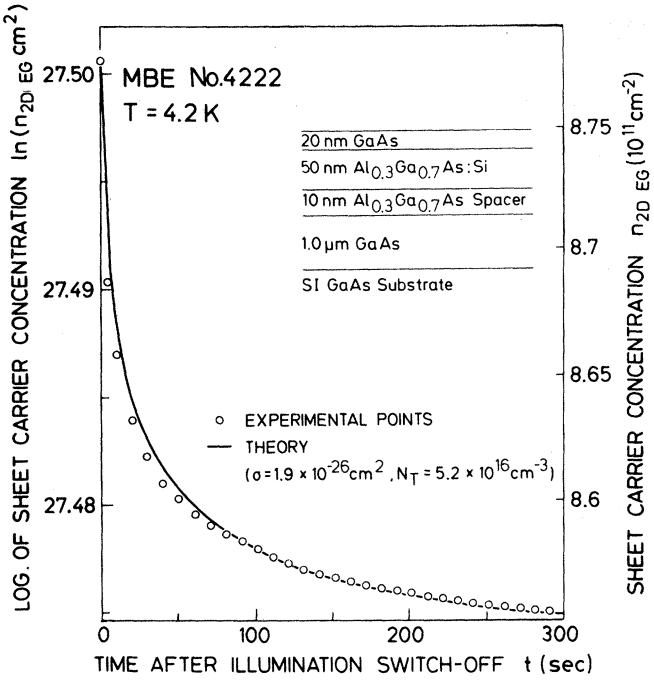

FIG. 6. Decay of the carrier concentration $n_{2D\,EG}$ measured by Hall effect at 4.2 K (sample no. 4222). The solid line depicts the results of the theoretical calculation using the parameters given in the figure.

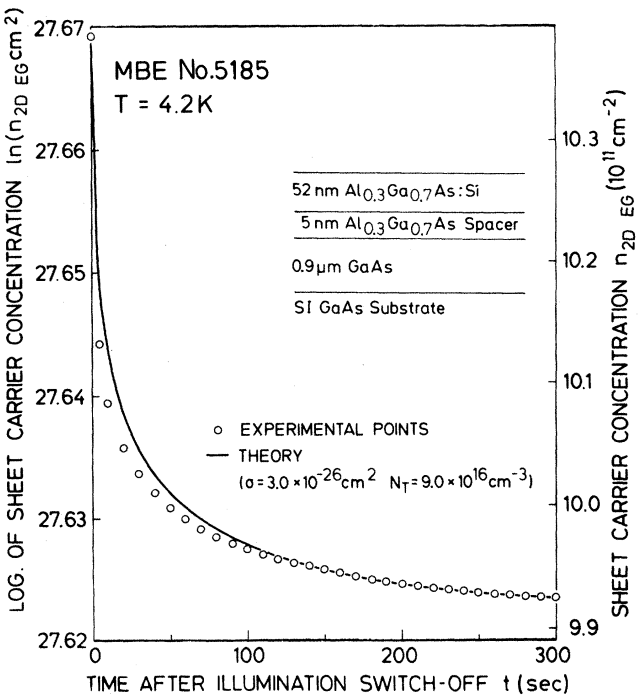

FIG. 7. Decay of the carrier concentration $n_{2D\,EG}$ measured by Hall effect at 4.2 K (sample no 5185). The solid line shows the results of the theoretical calculation using the parameters given in the figure.

and samples which were grown under different growth conditions. The concentration of the trap, however, varies from sample to sample and possibly depends on the growth conditions and on the composition of the $Al_xGa_{1-x}As$ alloy.[15] In the samples with $0.25 < x < 0.35$ investigated up to this point, we measured a concentration in the 10^{16}-cm^{-3} range.

Inspection of Figs. 6 and 7 reveals good agreement between the experimental points and the theoretical curve. For larger times ($100 < t < 300$ sec), theory and experiment agree excellently. For small times ($10 < t < 100$ sec), there are minor discrepancies between theory and experiment. They are probably caused by a nonhomogeneous distribution of traps in the $Al_xGa_{1-x}As$ layer. If the trap concentration in $Al_xGa_{1-x}As$ close to the interface is larger than in the bulk, the small deviation can be readily explained. A higher concentration of this kind of electron trap near the interface may be induced by the lattice mismatch between the binary and ternary semiconductor. From the good agreement found between experimental and theoretical decay we conclude that only one kind of trap is involved in the tunneling-assisted capture process.

The independence of the trap responsible for TPC from the *DX* center responsible for PPC is demonstrated by multiple-excitation experiments. The sample was illuminated, and then the carrier decay in the dark was monitored. Then the sample was illuminated again. This procedure was performed several times, and the observed time dependence of the carrier concentration is depicted in Fig. 8 for three cycles. The persistent part of the carrier-concentration enhancement increases steadily with the illumination dose. The transient part, however, remains the same after each illumination cycle. This result clearly indicates that the transient part of the concentration is independent of the persistent part of the carrier-concentration increase.

Tanoue and Sasaki[16] also performed time-resolved Hall measurements after illumination, but at temperatures from 77 to 300 K. In this temperature range the *DX* center responsible for PPC recaptures electrons. This trap, however, does not play a role in terms of recombina-

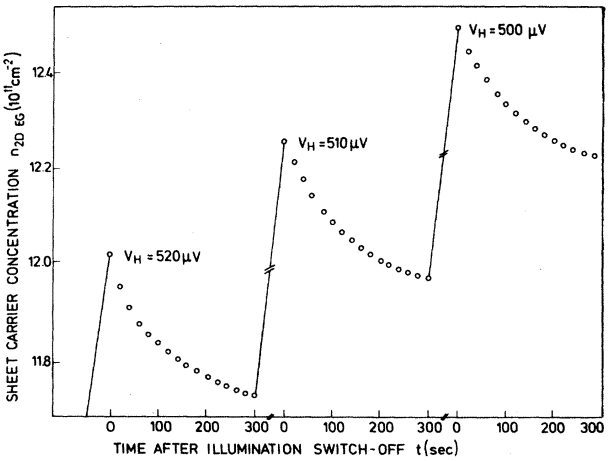

FIG. 8. The decay of the transient photoconductivity after several cycles of illumination. The persistent part of the carrier concentration is steadily increasing with the illumination dose.

tion at the low temperatures used in our experiments, as was noted by the authors.

B. Change of mobility

During the tunneling-assisted relaxation process, a change of the concentration of ionized traps occurs. Consequently, the scattering by remote ionized impurities of the 2D EG should be modified, and a change of the electron mobility is expected. In Fig. 9, we show the measured variation of the mobility in a representative selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructure at 4.2 K after the illumination is switched off. Shortly after the illumination is switched off, a drastic decrease of the mobility is observed. The difference of the mobility in the dark and during illumination is about 25%. This change was also reported by Drummond *et al.*,[17] but not explained by the authors. The mobility decrease during the relaxation process indicates that the trap changes its charge state from neutral to ionized, so that the scattering probability of electrons in the 2D EG by remote charged centers is enhanced, and the mobility decreases. From the observed decrease of the mobility, we conclude that the two charge states of the TPC trap are neutral if empty and negatively charged if occupied by an electron. Therefore, we assume that this specific trap is an acceptorlike center. It could also be a double acceptor, but this seems less probable.

Shortly after the illumination is switched off, electrons first recombine with traps located close to the interface, according to our theoretical model. This results in a strong Coulomb interaction of these negatively charged traps with the 2D EG. A drastic decrease of the mobility for short times is thus expected. At longer times, after the illumination is switched off, electrons recombine with traps further away from the interface. These traps in turn do not influence the electron mobility significantly, since their spatial separation from the 2D EG is large. Therefore, only a minor decrease of the mobility is expected.

These qualitative considerations are consistent with the experimental observations of the mobility decrease and support the model of tunneling-assisted recombination. A quantitative calculation of the mobility decrease and its comparison with experimental results is deferred to a subsequent paper.

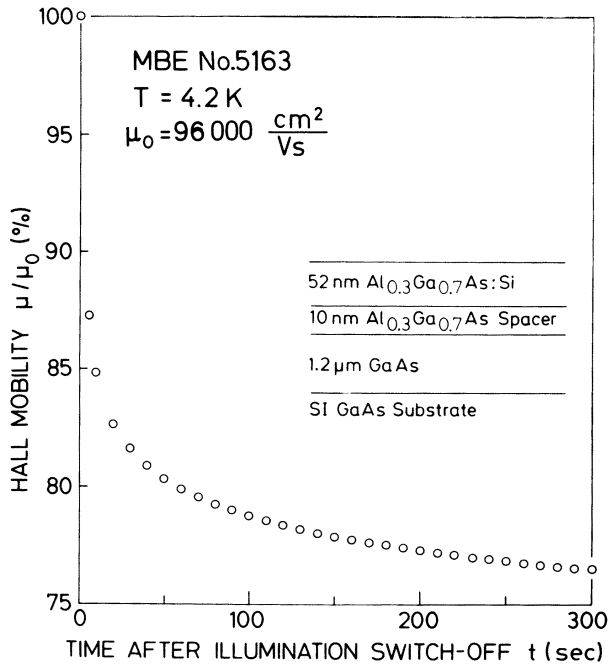

FIG. 9. Change of the Hall mobility observed in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ during the relaxation process.

V. CONCLUSION

We have analyzed a new kind of transient photoconductivity both experimentally and theoretically. The effect is observed as a decay of the 2D carrier concentration in selectively doped n-type $Al_xGa_{1-x}As/GaAs$ heterostructures after illumination at liquid-He temperature (4.2 K). Microscopically, the effect can be described as tunneling-assisted recombination of electrons with a deep trap near the interface within the space-charge region of the $Al_xGa_{1-x}As$. The ground-state energy of the TPC trap is at least 200 meV below the conduction-band edge of the $Al_xGa_{1-x}As$ layer. The TPC trap has the charge states neutral and negatively charged. It is an acceptorlike trap. The decay of the mobility during the relaxation process is due to an increased scattering rate by remote charged impurities and is qualitatively consistent with the theoretical model.

The concentration and the capture cross section of the TPC trap were determined for different samples by monitoring the decay of the photogenerated 2D electron concentration in the dark (TPCS). The concentration of the trap was measured in several samples and was found to be in the 10^{16}-cm^{-3} range. The capture cross section is at least 10^5 times larger than the capture cross section of the well-known DX center at this temperature (4.2 K). The TPCS method is a useful tool to characterize modulation-doped heterostructures in terms of deep-trap concentration, which in turn influences the electronic and optical properties of $Al_xGa_{1-x}As/GaAs$ interfaces. To our knowledge, TPCS is the only existing method to quantitatively determine the concentration of a deep trap near the interface within the space-charge region of a selectively doped n-type Al_xGa_{1-x} As/GaAs heterojunction. The TPC effect sheds more light on the physical properties of heterojunctions.

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[1]H. L. Störmer, A. Pinczuk, A. C. Gossard, and W. Wiegmann, Appl. Phys. Lett. 38, 691 (1981).
[2]K. von Klitzing, Surf. Sci. 113, 1 (1982).
[3]D. C. Tsui, H. L. Störmer, and A. C. Gossard, Phys. Rev. Lett. 48, 1559 (1982).
[4]G. Ebert, K. von Klitzing, C. Probst, and K. Ploog, Solid State Commun. 44, 95 (1982).
[5]D. Delagebeaudeuf and N. T. Linh, IEEE Trans. Electron Devices ED-29, 955 (1982).
[6]M. Abe, T. Mimura, N. Yokoyama, and H. Ishikawa, IEEE Trans. Microwave Theory Tech. MTT-30, 992 (1982).
[7]R. J. Nelson, Appl. Phys. Lett. 31, 351 (1977).
[8]D. V. Lang, R. A. Logan, and M. Jaros, Phys. Rev. B 19, 1015 (1979).
[9]H. Künzel, K. Ploog, K. Wünstel, and B. L. Zhou, J. Electron. Mater. (to be published).
[10]E. F. Schubert, K. Ploog, H. Dämbkes, and K. Heime, Appl. Phys. A 33, 63 (1984).
[11]B. L. Zhou, K. Ploog, E. Gmelin, X. Q. Zeng, and M. Schulz, Appl. Phys. A 28, 223 (1982).
[12]R. Fischer, D. Arnold, R. E. Thorne, T. J. Drummond, and H. Morkoc, Electron. Lett. 19, 200 (1983).
[13]F. Stern, Phys. Rev. B 5, 4891 (1972).
[14]T. Ando, J. Phys. Soc. Jpn. 51, 3900 (1982).
[15]H. Künzel, H. Jung, E. Schubert, and K. Ploog, J. Phys. (Paris) Colloq. 43, C5-175 (1982).
[16]T. Tanoue and H. Sasaki, in *Collected Papers of Molecular-Beam Epitaxy—CST-2* (Japanese Physical Society, Tokyo, 1982), p. 143.
[17]T. J. Drummond, W. Kopp, R. Fischer, H. Morkoc, R. E. Thorne, and A. Y. Cho, J. Appl. Phys. 53, 1238 (1982).