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Field induced carrier capture and optical release from traps in highly doped GaAs:Si

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Abstract. Carrier capture induced by electric fields in δ-like GaAs highly doped with Si is investigated with respect to the carrier heating necessary for such a charge transfer and the energy required to release the trapped carriers. The existence of a threshold field is established. The value of the threshold field for capture is in accordance with either trapping via the L band or a process that is direct but assisted by a large-wavevector phonon. The release of the carriers from the metastable traps due to infrared excitation, measured in terms of its dependence on the wavelength, yields a significantly higher threshold than is usually required for thermal excitation. This indicates the substantial lattice relaxation involved to form the charged trap.

1. Introduction

In GaAs/AlGaAs structures carrier capture in heating electric fields is known to lead to hysteresis of current–voltage characteristics [1–3]. This hysteresis of I–V characteristics was attributed to centres connected with the dopants. In a previous paper [4] we reported on such behaviour at 77 K for δ-like GaAs highly doped with Si. At high electric fields the current is reduced by up to 20% with increasing number of applied voltage pulses, and it can be shown that the current changes scale with the total duration of the applied field. Furthermore these current changes can be entirely prevented by illumination with a red light-emitting diode (LED). Generally, besides Si atoms acting as substitutionals on Ga sites—acting as shallow donors—metastable centres can be formed; this is reviewed in [5], for instance. They can be caused by a shift of the Si atom in the $\langle 111\rangle$ direction to an interstitial site, accompanied by either a substantial lattice relaxation or only a slight lattice relaxation. The metastable centres have been investigated in numerous experiments for thermal equilibrium; see, e.g., [6–15] concerning GaAs. In the present paper we firstly investigate the field dependence for the charge transfer and find the existence of a threshold field for carrier trapping; secondly, the spectral dependence of the carrier release caused by IR radiation is measured.

2. Samples and the experimental procedure

The δ-doped samples were prepared by molecular beam epitaxy on a GaAs(001) substrate. The doping was performed by the interrupted-deposition technique [16] at 570 °C, whereas

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the temperature was reduced to 530 °C during the growth of the cap layer (sample I). For details of sample preparation, see [4]. Via Hall and dc conductivity measurements we obtained an effective electron concentration of about 1×10^{13} cm^{-2} for a deposition of 2×10^{13} cm^{-2} Si atoms. Even if the total electron concentration is in fact somewhat higher than such an averaged value, it is demonstrated that only a proportion of the introduced dopants act as donors, while the others are electrically inactive, although Raman measurements reflect the fact that Si incorporated at Ga sites dominates among the possible configurations. In order to provide a basis for discussion of the influence of the donor concentration, the measurements were also performed on a sample doped with 7×10^{12} cm^{-2} Si atoms yielding an effective carrier density of 3.5×10^{12} cm^{-2} (sample II), as previously used in [4]. The sample geometry was defined by etching a mesa of 20 μm length and 135 μm width. The contacts were fabricated by alloying Au and Ge.

The current voltage behaviour was measured with the samples immersed in liquid nitrogen. The voltage was applied in pulses with a repetition rate of 1 to 10 Hz and a duration of 50 to 1000 ns. The wide region of pulse duration was chosen to investigate the scaling behaviour with respect to time. The upper limit was chosen in order to avoid thermal breakdown or even destruction of the sample. A 50 Ω resistor was mounted directly adjacent to the sample in order to determine the current. The voltage drops across the sample as well as the resistor were measured using a highly ohmic probe. The spectral dependence of the IR excitation was determined using a Nernst glower as the light source and a spectrometer. The measurements were performed in an optical cryostat with high-frequency equipment. Because the intensity of the Nernst glower was very weak an exposure time of 15 minutes was used. Therefore, a temperature of 4.2 K was chosen in order to reduce the background IR radiation.

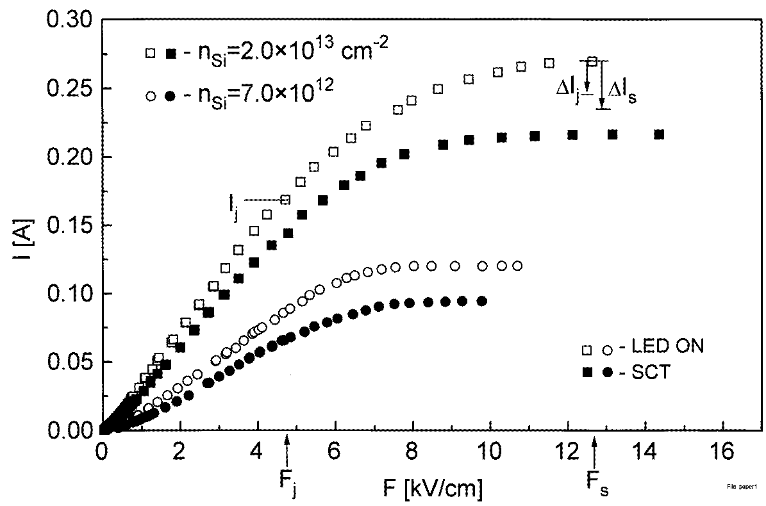

Figure 1. The current as a function of applied field at 77 K for samples I and II, respectively; open symbols: the initial state or under illumination; solid symbols: after saturation of carrier transfer (SCT). The current changes used for determination of the threshold field (see figure 2) are marked by arrows.

3. Hot-carrier capture

The current–voltage characteristics are demonstrated in figure 1. The saturation behaviour of the characteristics is typical for the Gunn effect in GaAs, with the threshold for saturation depending on the doping level. Furthermore, the effect of field induced carrier capture can clearly be seen. The curves depicted by open symbols are obtained after cooling the sample down in the dark and measuring the characteristics either using one single-voltage pulse of 100 ns duration for each point of the curve or under illumination by an LED with a wavelength of 0.66 μm without limitation of the repetition rate of the applied voltage pulses. The characteristics coincide for the two cases. The curves of solid symbols show the characteristics obtained after exposure of the sample in the dark to the electric fields for a long time, i.e. after saturated charge transfer (SCT) into a trap. Since only the electrons in the tail of the distribution function have the energy required to overcome the potential barrier of the trap, the capture process needs to proceed for some time to achieve saturation (scaling with the number of pulses $\times$ the pulse duration).

In order to determine the field dependence of the carrier transfer into the traps we proceeded in the following way. After illumination of the sample with the LED, i.e. removing the carriers from the traps, an initial current I_s flows through the sample for a given reference field strength F_s chosen in the saturation region of the characteristics. During a given duration Δt_s of application of the field (number of pulses $\times$ pulse duration), the current is changed by ΔI_s (see figure 1). After the traps have been charged in this way the initial state is again restored via illumination. Now, at a desired field strength $F_j < F_s$ for the corresponding current I_j (represented by open symbols in figure 1) the time Δt_j is determined, in which the same amount of charge flows through the sample as does at the field strength F_s during the time Δt_s; this is approximately given by $I_s f \Delta t_s / I_j$. The corresponding trapping is implemented at F_j by applying voltage pulses for the time Δt_j in the dark. Then, at the reference field strength F_s the corresponding current change $\Delta I_j(F_s)$ introduced by F_j during the time Δt_j is detected in a single-pulse measurement. This procedure compares the influence of equivalent charge flows at the field strength F_j and at the reference field strength in the saturation region of the characteristics. Such a cycle is repeated for the next selected field strength. The ratios of the current change $\Delta I_j(F_s)$ to the initially chosen ΔI_s are shown in figure 2 as functions of the field strength for both samples, I and II. It can be seen that this ratio increases substantially only above a threshold field strength which is somewhat less than the field necessary for the current saturation with respect to the Γ–L transfer (compare figure 1). In accordance with the latter, the threshold field for the carrier trapping also shifts to higher field values with increasing impurity density and, consequently, weaker carrier heating. The existence of the threshold indicates that a certain excess energy of the electron is necessary for the transfer into the centre and that the centre is positioned energetically distinctly above the Fermi level.

4. Carrier release from filled traps

As we reported in [4] the filled-trap state in our highly doped δ-layers is metastable and shows the large difference with respect to thermal and optical excitation usually expected for substantial lattice relaxation. When the heating field is switched off the centres do not become emptied at 77 K, but on heating the sample to room temperature and cooling it down again or illuminating it with a red LED at 77 K, the initially measured characteristics are restored. In order to obtain detailed information, in the present investigations the change of the trapped carrier concentration under illumination was determined as a function

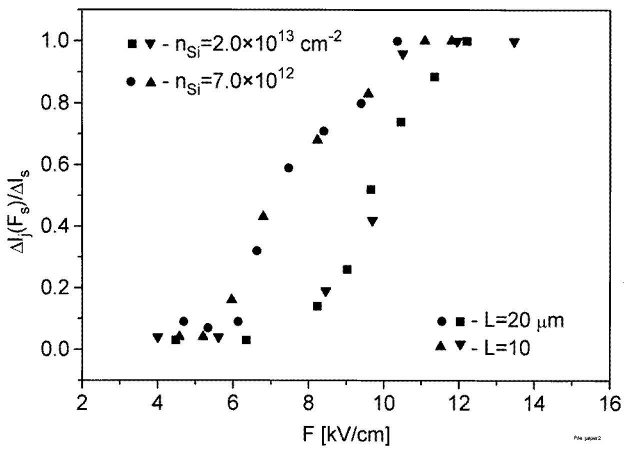

Figure 2. The threshold field for carrier capture determined from the ratio of the changes in current (compare with figure 1) versus applied field for samples I and II and for two different lengths.

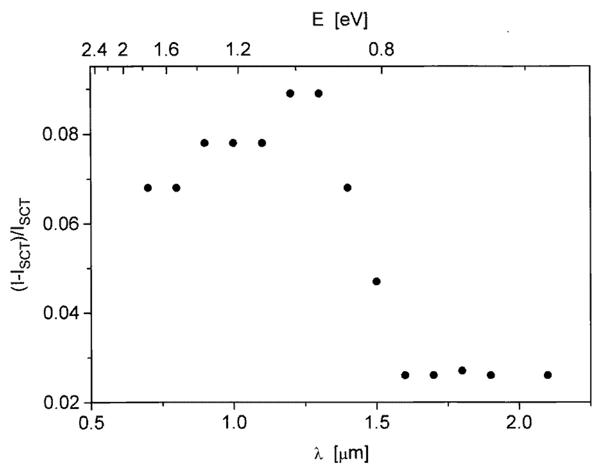

Figure 3. The current change normalized to the value for saturated carrier transfer in the saturation region at 4.2 K for sample I versus the wavelength of the excitation radiation.

of wavelength. After saturation of the carrier transfer to the traps (the characteristics represented by solid symbols in figure 1) was established, the current increase caused by IR radiation was measured in the single-pulse regime. The results depicted in figure 3 show a steep drop above 1.4 μm (equivalent to an energy of 0.9 eV). Due to the small intensity of the Nernst glower, full restoration of the current was not achieved in reasonable times. However, using a much more intense light source (application of a LED with $\lambda = 1.4$ μm) the initial state could be more rapidly restored. The threshold for ionization is in agreement with results in [10] and a reference in [17] to an optical ionization energy of 1 eV for a DX^- centre in GaAs. For the low-energy side, illumination with a halogen lamp with an edge filter with $\lambda \geqslant 2.2$ μm shows no effect within the sensitivity of our measurements.

5. Discussion

It should be emphasized that the critical field for current saturation demonstrates the onset of negative differential conductivity (ndc) at an already high percentage of carriers repopulated from the Γ minimum to the L valleys—about 75% according to a Monte Carlo simulation [18]. Of course, there is already a significant redistribution even for lower field strengths. Consequently, the threshold field observed for hot-electron trapping seems to be determined either by a transfer via the L valleys or directly from Γ to the metastable centre which has a smaller energy separation from the states populated in Γ than have the L valleys. Therefore, we conclude that the field induced trapping needs significantly less energy than is necessary to overcome the barrier of 550 meV stated for the thermally activated capture in the DLTS measurements for a 50 nm thick highly Si doped layer [10]. It should be noted, of course, that our experiments were performed far from thermodynamic equilibrium in contrast to the DLTS measurements. In the case of field induced transfer, both proposed types of capture are phonon assisted. In the first case optical phonons are required for the Γ–L transition via the deformation potential interaction—besides the phonons involved for the transition from the L valleys to the metastable centre. In the second case a large-wavevector phonon also seems to be demanded for the transition from Γ to the metastable centre. The carriers in the presence of a strong electric field gain enough energy (see [18] for instance) to emit the necessary phonons.

The above-mentioned difference as regards the necessary energy for field-induced and thermally activated carrier trapping adds one more item to the general discussion of DX centres, which can be characterized by the following arguments against and in favour of a link of the metastable centre to the L band. A transfer via L was also proposed in [19] to explain photoluminescence and photoconductivity in AlGaAs. Furthermore, studies of superlattices indicate a strong link of the centre of the L minimum [20]. On the other hand, an unambiguous conclusion in favour of the model with substantial lattice relaxation, according to negative-U centres [21], was apparently drawn from the different pressure coefficients of the centre and the L band in [8] and also from the pressure dependence of measurements of local vibrational modes [15].

Furthermore, the significantly higher energy value for photoionization in comparison to that for thermal activation of trapped electrons seems to prove the validity of the model with substantial lattice relaxation [10]. Such a big difference was reported for AlGaAs [22], too, but this was somewhat questionable because of an observed existence of two types of centre in those samples characterized by threshold energies of 850 and 225 meV, respectively [23]. In our samples the ionization threshold is approximately the same as that for the upper ionization threshold in AlGaAs; however, a second threshold could not be observed with the present set-up.

6. Summary

Summarizing, we confirm that for high doping densities in δ-layers metastable centres above the Fermi level are present. In contrast to the methodology of investigations performed on GaAs in thermal equilibrium up to now, which involved a decrease of the energy difference between the centre and the conduction band caused by pressure, in the present paper a high electric field is applied in order to increase the carrier energy. A new method is proposed to investigate under which conditions the hot electrons are enabled to become captured. The existence of a threshold field for the carrier transfer to the centres could be established and its value appears to be slightly below the onset of current saturation due to

Γ–L transitions. Therefore, we propose that this process either may involve a transition via the L band or proceeds directly but with the assistance of a large wavevector phonon—in contrast to a thermally activated transfer from Γ over a high potential barrier. Consequently we conclude that the effective barrier for field induced transfer is significantly lower than the value of 550 meV for thermal equilibrium deduced from measurements of capacitance transients. From the spectral dependence of the influence of IR radiation on the current change, the necessary energy for optical excitation of electrons from the trap is deduced to be about 0.9 eV: the apparent significant difference between the energies required for thermal and optical carrier release supports the model of substantial lattice relaxation, which is usually ascribed to the DX^- centre. Our observations and the other facts mentioned above demonstrate the nature of the DX centre in GaAs is still not completely understood.

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