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Doping and Temperature Dependence of Carrier Lifetime in 4H SiC Epitaxial Layers

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Abstract. Thick 4H-SiC epilayers have be grown with n-type and p-type doping in the range $1x10^{14}$ cm^{-3} to mid $1x10^{18}$ cm^{-3}, with the purpose of investigating the influence of doping on carrier lifetime. Growth conditions were identical for all grown epilayers, except for the dopant gas flow rates. A drastic decrease in carrier lifetime was observed with increasing doping level, in both n-type and p-type layers. The decrease in lifetime could not be related to the $Z_{1/2}$ center but are rather due to an enhanced effect of direct band-to-band and Auger recombination's (AR) at higher doping levels. Calculations of Auger coefficients for the recombination's are indicating Auger recombination's as the main recombination mechanism at the highest doping levels. Indications are made stronger from the temperature dependence of Auger coefficients. An increased background intensity arises around 400 K during temperature dependent time-resolved photoluminescence measurements of n-type epilayers are observed and are thought to be related to boron impurities.

Introduction

The unique properties of silicon carbide (SiC), such as its wide bandgap, high thermal conductivity and high breakdown electric field strength makes it a suitable candidate for high power devices. An important material parameter of the semiconductor is the minority carrier lifetime, which is sensitive to the purity of the semiconductor material and a very critical parameter for materials intended for use in high power devices.

To minimize the forward-voltage drop in high-power bipolar devices, a long carrier lifetime is required. Many published studies on the carrier lifetime in SiC are made on thick low doped epitaxial layers, since such layers are required for high voltage blocking devices. However, the carrier lifetime is also of great importance in highly doped epilayers in different device structures. Minority carrier lifetime measurements require thick epitaxial epilayers to minimize the influence of diffusion out of the region or at the surface. To the best of our knowledge, very few carrier lifetime studies have been conducted in the combination of thick and highly doped, n-type and p-type, epilayers.

Carrier lifetime is one of the most important parameters regarding device performance and the main lifetime limiting defect has been identified as the $Z_{1/2}$ center [1]. The $Z_{1/2}$ center has been attributed to the isolated carbon vacancies (V_C) with negative-U properties [2]. Apart from the Shockley-Read-Hall (SRH) recombination via the $Z_{1/2}$ center the lifetime is also limited at high carrier concentrations by the Auger process, where the energy in an electron-hole recombination is transferred to a third carrier. In highly doped epilayers, the Auger recombination's are the ultimate limit to long carrier lifetimes [3].

Auger recombination (AR) rates can be determined from carrier concentration transients by evaluating minority carrier lifetimes in heavily doped semiconductors under low injection conditions [4]. In addition of only being lifetime limiting, enhanced Auger recombination's in highly doped buffer layers have shown to be a solution to prevent the Shockley stacking fault (SSF) expansion from basal plane dislocations (BPDs) [4]. It is shown that to avoid the expansion of SSFs from BPDs in 4H-SiC one need to decrease the density of injected minority carriers in the areas where BPDs exist, which can be done by enhancing Auger recombination's by high nitrogen doping densities. Thus, to avoid SSF formation near the epilayer/substrate interface, the authors showed that a thin highly doped layer could be grown between the n^- drift layer and substrate [4].

Experimental

In this paper, different series of n- (N1 and N2) and p-type (P1) epitaxial layers were grown with a doping in the range from $1x10^{14}$ cm^{-3} to mid $1x10^{18}$ cm^{-3} on the minority carrier lifetime are studied. The epitaxial layers were grown in a Aixtron VP508 reactor with gas foil rotation using standard chemistry with Silane (SiH_4) and propane (C_3H_8) with hydrogen (H_2) carrier gas. The doping was obtained with nitrogen gas (N_2) for n-type epilayers and trimethylaluminum (TMA) for p-type epilayers. Epilayers were grown on 4H-SiC (0001) substrates, with an off-cut angle of 4° towards [11$\bar{2}$0], with identical growth conditions in each doping series except for the gas flow rates of the dopants. All epilayers in all series were grown to a nominal thickness of 80 µm as measured by Fourier transform infrared reflectance spectroscopy (FTIR). Doping concentrations revealed by capacitance-voltage (C-V) measurements using a mercury probe station.

The carrier lifetime was determined from Time-resolved photoluminescence (TRPL), both at room temperature and temperature dependent measurements up to 500 K, using the photon counting technique. This is very useful in the present study since we observe and analyze multiple decay constants, and the photon counting technique provides an excellent signal to noise ration and makes it possible to analyze decay curves with multiple decay constants with different time constants. Free carriers were created by optical excitation using a frequency tripled pulsed Nd-YAG laser with emission at 355 nm and detected by a photomultiplier tube (PMT). All measurements were done a low injection, conditions with an excitation density of $1x10^{15}$ cm^{-3}. Decay constants were extracted from the photoluminescence decay at the bandgap (selected with a bandpass filter) after the pulsed excitation.

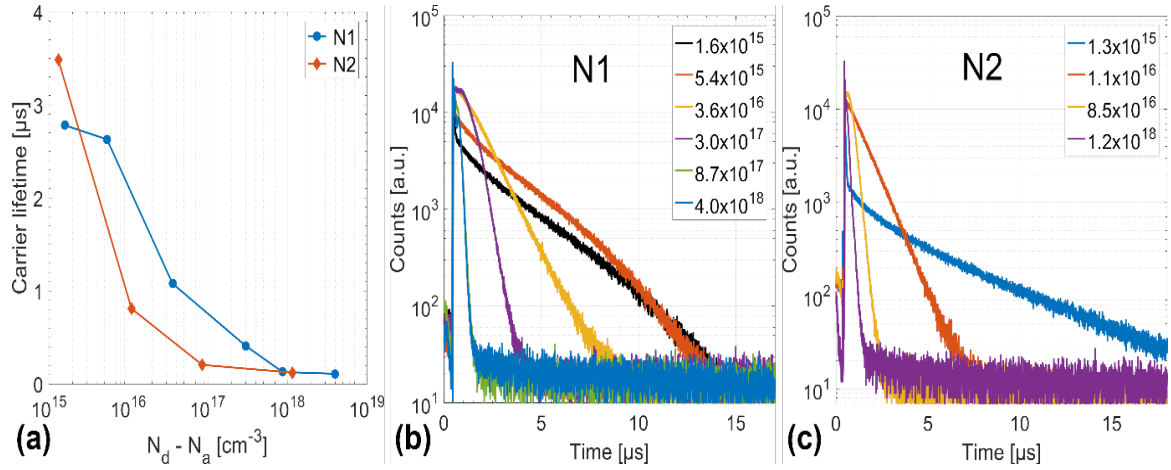

Fig. 1. (a) Measured carrier lifetime as a function of n-type doping for series N1 and N2. The carrier lifetime decreases with increasing n-type doping, with the most significant lifetime drop in the range $1x10^{16}$ - $1x10^{17}$ cm^{-3}. (b) and (c) shows the corresponding decay curves for both series.

Experimental Results

For both n-type series (N1 and N2) and p-type series (P1) a significant decrease in carrier lifetime occurs when increasing the doping concentration. Generally, starting at about 2 – 3 µs for the lowest doping concentration and decreasing to about 0.1 µs for doping concentrations in the 10^{18} cm^{-3} range. Increasing the **n-type doping** from $1x10^{15}$ cm^{-3} to mid $1x10^{18}$ cm^{-3}, the measured carrier lifetimes decrease from around 3 µs down to about 0.1 µs, as shown in Figure 1 (a). The decay transients as measured by TRPL, are shown in Figure 1 (b) and (c) for series N1 and N2, respectively. A maximum carrier lifetime is observed for the lowest doped samples (~$1x10^{15}$ cm^{-3}). At higher n-type doping densities, a significant decrease in measured carrier lifetime occurs, but the carrier lifetime stagnates at around 0.1 µs for n-type doping densities of about $1x10^{18}$ cm^{-3} and higher. DLTS measurements were performed on the samples in the N1 series and showed a constant $Z_{1/2}$ concentration of around

$5x10^{11}$ cm^{-3} for doped samples up to $3.6x10^{16}$ cm^{-3}, despite the drastic reduction in measured lifetime. For the higher doped samples the measured concentration was below the detection limit.

All the measured decay curves, as shown in Figure 1 (b) and (c), have an almost exponential decay. However, the lowest n-type doped decay curves have a slightly different shape, indicating that several recombination phenomena are present in those layers. Shockley-Read-Hall (SHR) recombinations (via deep levels) are normally the dominant recombination at low-level injection conditions together with surface recombinations in lower doped epilayers. With increasing n-type doping concentration in the epilayers we speculate that more Auger recombinations occur, which otherwise would be expected at high-level injection conditions in lower n-type doped epilayers. We believe that the recombination in highly n-type doped epilayers with high electron concentrations is dominated by Auger recombinations, even at low-level injection conditions. Thus, the highly doped n-type epilayers have stronger effect from Auger recombinations than of SRH recombinations, as also discussed by Tawara et al.[4]

Increasing the **p-type doping** from $2.1x10^{14}$ cm^{-3} to $1.0x10^{18}$ cm^{-3}, the measured carrier lifetime decreases from above 2 µs down to about 0.1 µs, as shown in Figure 2 (a). The decay transients as measured by TRPL are shown in Figure 2 (b) for p-type series P1. A maximum carrier lifetime of 2.1 µs is observed for the lowest doped epilayer, with a p-type doping of $2.1x10^{14}$ cm^{-3}. For increasing p-doping concentrations a drastic decrease in carrier lifetime occurs up to a p-type doping concentration of about mid $1x10^{16}$ cm^{-3}, where the carrier lifetime has dropped below 0.2 µs and then slowly decreases to 0.1 µs for a p-type doping of $1.0x10^{18}$ cm^{-3}.

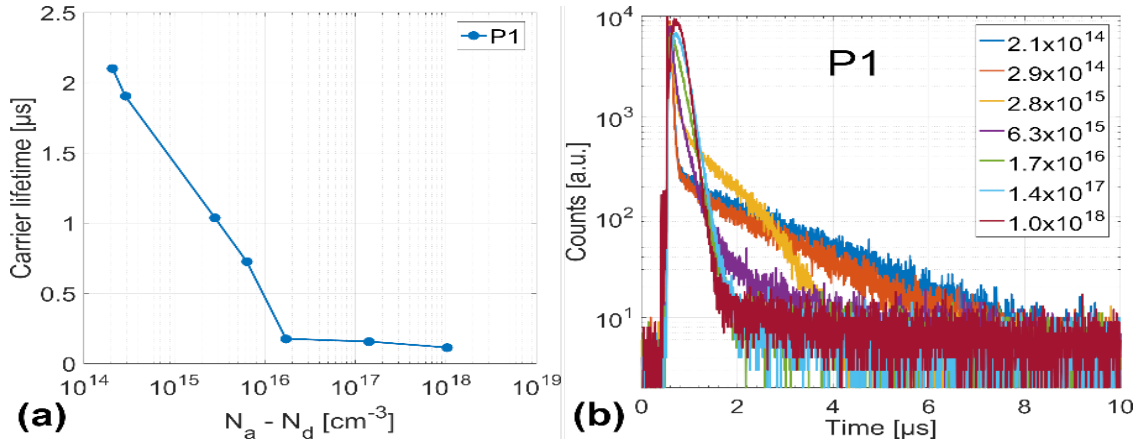

Fig. 2. (a) Measured carrier lifetime as a function of p-type doping for series P1. The carrier lifetime decreases with increasing p-type doping, with the most significant lifetime drop in the range $1x10^{15}$ - $1x10^{16}$ cm^{-3}. (b) shows the corresponding decay curves.

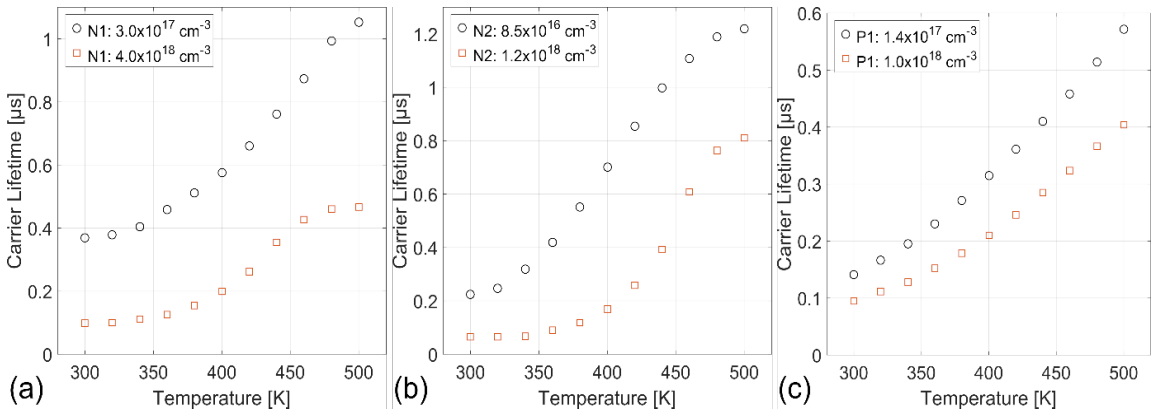

Fig. 3. Carrier lifetime as a function of TRPL measurement temperature, 300 K to 500 K, for the two epilayers with highest doping concentration from each of the series; (a) N1, (b) N2 and (c) P1.

As compared to our results in the n-type doping series, the carrier lifetime of the p-type epilayers is somewhat lower and decreases more rapidly at higher doping concentrations. We believe that there are several reasons for the observed difference. Both the n-type and p-type series are measured under identical low-level injection conditions ($1x10^{15}$ cm^{-3}), and at such conditions the ambipolar diffusion constant is different between p-type and n-type epilayers.[5] For p-type, the diffusion is enhanced under low-level injection conditions and thus the carrier recombination at the surface and in the substrate is pronounced and the effective carrier lifetime is lowered. For n-type samples, the ambipolar diffusion constant is instead decreased under low-level injection conditions, which reduces carrier diffusion towards the surface and substrate and the effective carrier lifetime is enhanced. Thus, the difference in diffusion constant of the minority carriers for n-type (holes) and p-type (electrons) causes a difference in measured carrier lifetime.[5] Hayashi et al. speculate in insufficient elimination of $Z_{1/2}$ center as a reason for weaker lifetime enhancements in p-type.[6] There is also speculations if there is more than one recombination center in p-type epilayers besides the V_C-based center.[7]

Temperature dependent TRPL investigations were performed for both the n-type and p-type epilayers. Generally, both the n-type and p-type series showed very similar temperature dependence of the decay constants, which are constantly increasing with temperature, indicating $Z_{1/2}$ as the main lifetime killer in both n-type and p-type epilayers.[9] In order to find possible reasons for the drastic lifetime drop with increasing doping concentration (when SRH recombinations via the $Z_{1/2}$ center might no longer be the main recombination mechanism), both n-type and p-type, temperature dependent carrier lifetime measurements were performed (in combination with DLTS/MCTS studies). The general phenomena observed during temperature dependent TRPL measurements in the range 300 K to 500 K, is constantly increasing decay constants for both n-type and p-type epilayers with increasing temperature as can be seen in Figure 3. The figure shows the carrier lifetimes as a function of temperature for the epilayers with highest doping concentration in series N1, N2 and P1. The $Z_{1/2}$ center exists in almost constant a concentration of $5x10^{11}$ cm^{-3} in the epilayers and most likely is the main recombination mechanism for the lower doped epilayer, but not responsible for the decreased carrier lifetime at higher doping concentrations.

During temperature dependent TRPL measurements in the high n-type doped epilayers, an **additional decay component** observed at temperatures of about 400 K as shown in Figure 4. This is first seen as an increased background corresponding to a very long decay, but at even higher temperatures with an increasingly faster decay constant. This background is not seen in low doped n-type epilayers or p-type epilayers. The additional decay component is only observed when detecting the bandgap emission (390 nm) and not below the bandgap (415 nm).

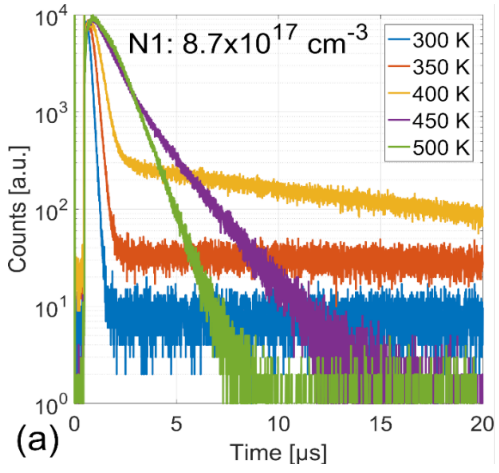

Fig. 4. Decay curves at higher Temperatures, 300-500K, for a n-type sample doped with $4.0x10^{18}$ cm^{-3}

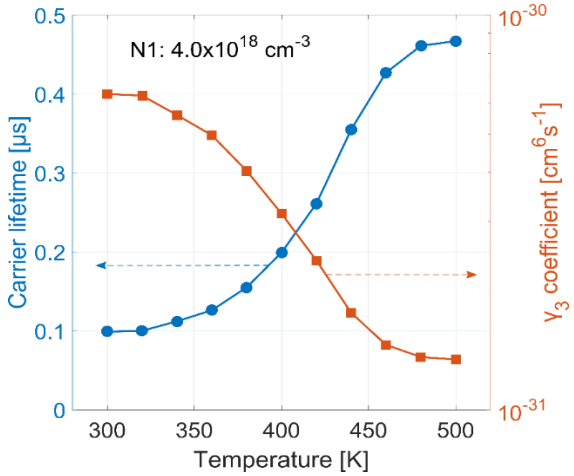

Fig. 5. Carrier lifetime and AR coefficient γ_3 as a function of temperature during TRPL measurements.

We believe this component is related to holes thermally released from deep acceptor states. One possible candidate could be the deep boron related D-center, since residual concentrations of boron can be seen in SIMS measurements in these samples.

Discussion

Since both n-type and p-type show the same tendencies in decay constants with temperature, most likely the same recombination centers are limiting the carrier lifetime. For lower doped layers, the $Z_{1/2}$ dominates and SRH recombinations control the carrier lifetime. For higher doped layers, the Auger recombinations take over as the main lifetime limiting recombination. Despite the recombination mechanism, SRH via $Z_{1/2}$ center or Auger recombination, the carrier lifetime increases with increasing measurement temperature.[3, 4, 10]

From the dependence of the carrier concentration, the minority carrier lifetime can be expressed as: $\tau^{-1} = \gamma_1 + \gamma_2 N + \gamma_3 N^2$, where τ is the minority carrier lifetime, N is the majority carrier density and the coefficients γ_1, γ_2 and γ_3 represents the monomolecular (SRH), bimolecular (direct band-to-band recombination) and AR rates.[3, 4] Calculations on only the AR coefficient (γ_3) have been made and for such calculations to be relevant, the assumption must be that the main recombination occurs through Auger recombination which might be the case for the most highly doped sample (N1, $4.0\text{x}10^{18}$ cm^{-3}). Auger recombination involves either two electrons and one hole (e-e-h AR) or two holes and one electron (h-h-e AR), in n-type and p-type respectively.[11] For the highly n-type doped epilayers, the e-e-h is the dominant recombination mechanism, and the hole lifetime is given by $\tau^{-1} = \gamma_3 N^2$. From this it is possible to calculate the AR coefficient, γ_3, from the TRPL measurements, since the carrier lifetime (τ) is extracted while knowing the doping concentration (N) of the epilayer. For the highest doped epilayer (N1, $4.0\text{x}10^{18}$ cm^{-3}) the carrier lifetime at 300 K is $\tau = 0.10$ µs, giving an AR coefficient of $\gamma_3 = 6.3\text{x}10^{-31}$ cm^6s^{-1}, which is in good agreement with Galeckas et al[3] . Increasing the TRPL measurement temperature from 300 K up to 500 K, an increased carrier lifetime (0.10 µs to 0.47 µs) is observed as can be seen in Figure 5 together with the AR coefficient γ_3 variation with temperature. A significant reduction of the AR coefficient from $6.3\text{x}10^{-31}$ cm^6s^{-1} to $1.3\text{x}10^{-31}$ cm^6s^{-1} for the temperature range 300 K to 500 K is observed, which is in agreement with results of Galeckas et al. and Tawara et al.[3,4]

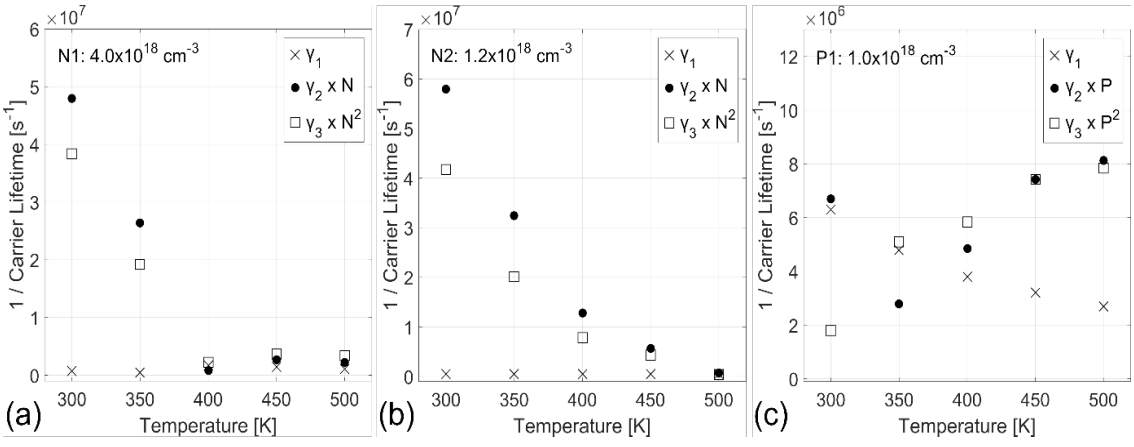

Fig. 6. Temperature dependence of the three recombination terms γ_1, γ_2 and γ_3 for relative highly doped epilayers; (a) $4.0\text{x}10^{18}$ cm^{-3} (series N1), (b) $1.2\text{x}10^{18}$ cm^{-3} (series N2) and (c) $1.0\text{x}10^{18}$ cm^{-3} (series P1).

The temperature dependence of the carrier lifetime and AR coefficient γ_3 in our highest doped epilayer makes it likely that Auger recombination is a main recombination mechanism at high doping concentrations.

For calculations on Auger recombinations to be relevant for epilayers with lower doping concentrations, such as the n-type epilayer $1.2\text{x}10^{18}$ cm^{-3} (N2 series) and the p-type epilayer

$1.0x10^{18}$ cm^{-3} (P1 series), the full expression of carrier lifetime must be used: $\tau^{-1} = \gamma_1 + \gamma_2 N + \gamma_3 N^2$. Values of γ_1, γ_2 and γ_3 have been extracted for temperatures 300 K, 350 K, 400 K, 450 K and 500 K for the three most highly doped samples in each of the series N1, N2 and P1. Those are then used to plot the temperature dependence of each recombination term for the highest doped samples in each series, see Figure 5, with the purpose of finding the main recombination mechanism dominating the carrier lifetimes. It is obvious that SRH recombinations are of low importance for doping concentrations above $1x10^{18}$ cm^{-3}, instead the effect of direct band-to-band and Auger recombinations becomes strong. Reaching to $4x10^{18}$ cm^{-3} (Figure 6b) Auger recombinations becomes the dominant recombination mechanism at higher TRPL measurement temperatures. Thus, our previous assumption that the Auger recombinations are dominant in the epilayer $4.0x10^{18}$ cm^{-3} (series 1), is valid at least in a temperature range of 400 – 500 K. For even higher doping concentrations reaching the $1x10^{19}$ cm^{-3} range, Auger recombinations will most likely dominate the carrier lifetimes [3,4]. In Figure 6c, the effect of the different recombination mechanisms in a p-type epilayer is shown, which has a larger contribution from SRH recombinations at lower temperatures compared to n-type epilayer (Figure 6b) with similar doping concentration. At higher temperatures the effect of both direct band-to-band and Auger recombinations are dominant.

Summary and Conclusions

Thick epilayers have been grown with doping concentrations ranging from low $1x10^{14}$ cm^{-3} to mid $1x10^{18}$ cm^{-3}, both n-type and p-type, with the purpose of investigating the influence on the carrier lifetime and recombinations responsible for the lifetime variations. Independent of doping type, a drastic decrease in carrier lifetime is observed with increasing doping concentrations. Auger recombinations are thought as the main recombination mechanism at the highest doping concentration ($4x10^{18}$ cm^{-3}) and the assumption is made likely from calculations on Auger coefficients. At doping concentrations in the $1x10^{18}$ cm^{-3} range, the effect of both direct band-to-band and Auger recombination are strong.

The deep level $Z_{1/2}$ has been confirmed as not responsible for the lifetime drop with increasing doping concentration. An additional decay component during temperature dependent TRPL measurements (at about 400 K) are observed in the n-type epilayers and are thought to be related to thermal release of holes to the valence band, which could be related to boron impurities originating from reactor parts

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