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The impact of defects to minority-carrier dynamics in heavily doped GaAs:C analyzed by transient photoluminescence spectroscopy

J.W. Tomm [a,*], A. Maaßdorf [b], Y.I. Mazur [a], S. Gramlich [b], E. Richter [b], F. Brunner [b], M. Weyers [b], G. Tränkle [b], V. Malyarchuk [a], T. Günther [a], Ch. Lienau [a], M. Jurisch [c]

[a] *Max-Born-Institut, Nichtlineare Optik Ber. C2, Max-Born-Strasse, 2A, D-12489 Berlin, Germany*
[b] *Ferdinand-Braun-Institut, Albert-Einstein-Strasse, 11, 12489 Berlin, Germany*
[c] *Freiberger Compound Materials, 09599 Freiberg, Germany*

Abstract

We report photoluminescence decay time measurements in heavily Carbon-doped GaAs epilayers which are designed for the application in heterojunction bipolar transistors. These data provide access to carrier lifetimes that determine the current gains, i.e. amplification of the devices. At room-temperature trapping of non-equilibrium carriers into deep levels may govern the recombination behavior, particularly for low excitation levels. Experimental conditions are determined that allow both to achieve trap saturation and to avoid stimulated emission. Detection must be limited to a spectral window well above the energy gap. Our time-resolved data are explained by intrinsic Auger and radiative recombination mechanisms as well as defect-related recombination and trapping.

Keywords: Photoluminescence; Gallium arsenide; Carbon; Doping effects; Epitaxy of thin films; Semiconductor device

1. Introduction

Heterojunction Bipolar Transistors (HBTs) with a heavily p-doped GaAs:C base region ($p_0 = 1–6 \times 10^{19}$ cm^{-3}) are of great practical importance in many application such as in cellular phones. The HBT current gain is proportional to the minority-carrier lifetime (τ) within the base of those transistors. Device lifetime and reliability are strongly affected by the minority-carrier lifetime, too [1]. Consequently, measurement of non-equilibrium-carrier kinetics at room-temperature, i.e. the operation temperature of the HBT, and subsequent control of this parameter by adjustment of epitaxial growth parameters are crucial requirements for optimizing HBT device production. A convenient way to access τ is by the analysis of transient photoluminescence (PL) after short impulsive laser excitation, such as reported in Refs. [2–6], predominantly for free layers. In this paper, we report on analysis of transient PL data from passivated GaAs:C-layers, i.e. layers that are sandwiched between wider gap cladding materials.

2. Experimental

Sub 100 fs laser pulses are used for interband excitation of the samples. The wavelength is 735 nm and the repetition rate 82 MHz. PL detection is done by a synchro-scan streak camera. Non-equilibrium carrier densities up to $\delta n = 10^{18}$ cm^{-3} are generated by each pulse. Spectral discrimination is provided by a 0.25 m monochromator. The over-all temporal resolution of the setup is better than 20 ps.

The double-heterostructures investigated are grown by metal–organic chemical vapor deposition in a horizontal Aixtron AIX200 reactor on GaAs substrates. Trimethylgallium (TMGa, $Ga(CH_3)_3$) as a group-III precursor and Arsin (AsH_3) enable intrinsic incorporation of carbon into the GaAs layers by choosing a V/III-ratio near unity for a growth temperature below 600 °C. Typical doping concentrations are in the 1

* Corresponding author. Tel.: +49-30-6392-1453; fax: +49-30-6392-1459.
E-mail address: tomm@mbi-berlin.de (J.W. Tomm).

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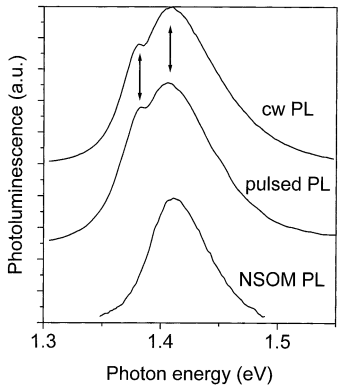

Fig. 1. Room-temperature 'regular' (top and center) and NSOM based (bottom) PL spectra. 'Regular' PL is excited by cw (top) and pulsed (center) lasers. The excitation light passes through the wider gap top cladding and created an excitation spot of $\phi = 200$ μm at the GaAs:C layer, whereas the NSOM based cw PL experiment is done directly at the GaAs:C at a freshly cleaved sample edge.

6×10^{19} cm^{-3} range. Two groups of samples are grown, either with $Ga_xIn_{1-x}P$ or $Al_xGa_{1-x}As$ barriers. The $Ga_xIn_{1-x}P$ barriers are grown at 580 °C with a mole fraction of $x = 0.51$ in order to achieve lattice-matching with the GaAs. The $Al_xGa_{1-x}As$ barrier layers have a composition of $x = 0.28$. A total of about 150 samples are measured.

3. Results and discussion

Fig. 1 shows three room-temperature PL spectra from a GaAs:C layer measured with time-integrating detection. The spectra at the top and bottom are excited by a cw laser, whereas the one in the center is measured after fs-pulse excitation. After having compared the PL spectra of several samples for cw and impulsive excitation we find no systematic differences between them. We consider this a strong indication that, under our experimental conditions, fs-excitation does not cause additional carrier heating effects. Furthermore, the effective carrier temperatures, estimated from the high-energy tails of the pulsed PL spectra, are found to be close to ambient temperature. The spectrum at the bottom was measured by collecting the PL via the fiber tip of a Near-field Scanning Optical Microscope (NSOM) directly at the GaAs:C-epilayer at a freshly cleaved sample edge. Obviously, the prominent double structure, cf. arrows in Fig. 1, being typical for GaAs:C-epilayers, cf. also Refs. [7–9], is absent for this microscopic geometry. Since the NSOM-based measuring geometry substantially reduces the pick-up of PL emission that is back-reflected from the reverse side of the substrate, we are able to identify the PL double peak to be due to multiple reflections including reabsorption effects in the substrate, i.e. as sample geometry effect, see Refs. [8,9].

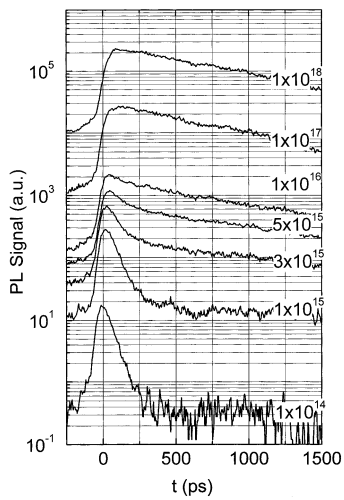

Fig. 2. Room-temperature transient PL data. The parameter is the excitation density in carrier pairs per pulse.

We should mention that the use of transient PL for the determination of non-equillibrium carrier kinetics relies on the assumption of a linear relationship between PL signal and non-equilibrium carrier density. This is only valid if stimulated emission as potential non-linear PL contribution is avoided. In a series of PL experiments at low temperatures and by using GaAs:C samples in a 90° excitation geometry we demonstrate the presence of stimulated emission. Then we extrapolate these data down to an excitation density of 1×10^{18} cm^{-3} per pulse and up to room temperature and show that under these conditions there is no interfering PL contribution caused by stimulated emission.

After having discussed several methodical issues connected with the use of PL as measure for non-equilibrium carrier dynamics we now directly address transient PL data. Fig. 2 shows typical PL transients. The parameter is the excitation density in carriers per cm^{-3} and per pulse. Note the presence of a fast but saturable recombination mechanism for low excitation densities. The presence of this mechanism is more or less pronounced for each individual sample with a tendency that is stronger for the samples where the GaAs:C layer is sandwiched between $Ga_{0.51}In_{0.49}P$. Note that the effect is also found for the bulk reference samples, at least at room temperature. Together with the finding about the non-radiative nature of the quick transient this is an indication for trapping into levels that are most likely created by interface or surface (for bulk) states. The latter assignment is proved in a set of experiments with intentionally treated surfaces from the same bulk crystal, where a clear correlation between surface quality and trapping time is demonstrated, see Ref. [10]. Thus we should note that for obtaining reproducible transient PL data it is essential to perform the room-temperature PL measurement at sufficiently high excitation densities, e.g. at 1×10^{17} cm^{-3} per pulse. The time constant determined in this density

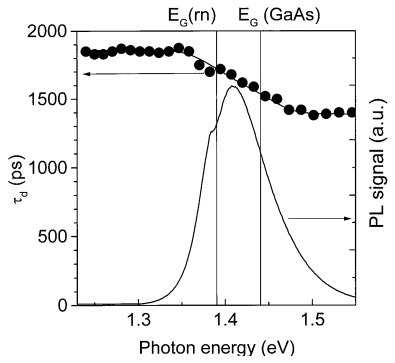

Fig. 3. Room-temperature PL decay time versus photon energy. For comparison a PL spectrum is added.

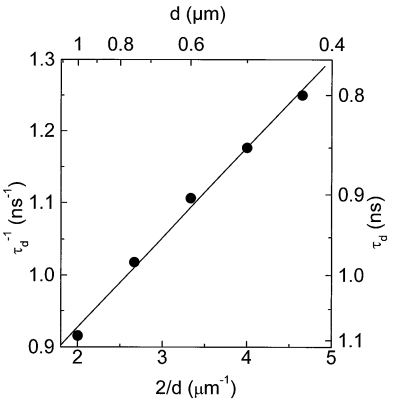

Fig. 4. Inverse PL decay time versus reciprocal sample thickness for a set of 5 samples with a carbon concentration of 10^{19} cm^{-3}. From the linear fit we obtain $\tau = 1.6$ ns and $S = 1.4 \times 10^4$ cm^{-1}.

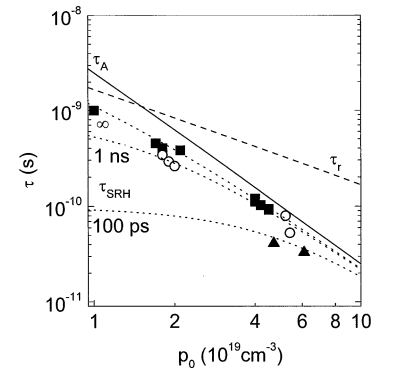

Fig. 5. Non-equilibrium carrier lifetimes τ versus carrier concentration for 15 sample sets derived from τ_d data. The sample sets are grown using TMG + AsH_3 (squares), TMGa + AsH_3 + CBr_4 (open circles) and TMGa + TMAs (full triangles) as GaAs:C precursors. Radiative (dashed line) and Auger (full line) recombination lifetimes are calculated according to [6]. The dotted lines represent the total lifetime according to (Eq. (2)) where a Shockley–Read–Hall lifetime of ∞, 1000 and 100 ps is assumed (from the top to the bottom).

regime from the linear slope of the semi-logarithmic plot (Fig. 2) will be called PL decay time (τ_d).

Fig. 3 shows the spectral dependence of τ_d together with the PL spectrum. The positions of the energy gaps (E_g) of GaAs and band-gap-renormalized GaAs [E_g(rn)] are indicated, too. Across the luminescence band, the PL decay decreases from 1.85 ns for photon energies below 1.35 eV to 1.4 ns at energies above 1.5 eV. This indicates that intrinsic minority carrier recombination dynamics might be studied rather in the plateau region above 1.5 eV. We tentatively assign the increasing PL decay times at lower photon energies to carrier recombination out of localized states in the density of states tail below E_g. However, there are competing interpretations and further work must be done to clarify this. Nevertheless one should note that spectrally integrated τ_d-measurements as well as those which are recorded at the low energy side of the PL peak are strongly influenced by extrinsic effects and so we suggest that PL detection should be restricted to a spectral window well above the gap ($E > 1.5$ eV).

Despite our attempts to reduce the impact of extrinsic effects on τ_d surface effects still affect the data. Fig. 4 shows a plot of the reciprocal PL decay time versus inverse sample thickness. The data show a clear reduction of the PL decay time with decreasing layer thickness, indicating that surface recombination is still relevant. Within the standard model outlined in Ref. [11] the layer thickness dependence of the PL decay times is given by:

$$1/\tau_d = 1/\tau + 2 \times S/d, \quad (1)$$

where τ indicates the intrinsic lifetime of the material, S the surface recombination velocity and d the layer thickness. Assuming a constant value of τ for all samples we find good agreement between experiment and model for $\tau = 1.6$ ns and $S = 1.4 \times 10^4$ cm^{-1}. A detailed description of these experiments is published elsewhere [3].

By taking into account the methodical findings discussed so far it should be possible to obtain improved access to the recombination behavior in our samples. This makes it interesting to investigate the dependence of the carrier lifetime on other parameters such as the Carbon doping technique or the doping concentration p_0. Results of such sets of experiments are summarized in Fig. 5 together with the calculated density dependencies of the intrinsic radiative recombination (τ_r, dashed line) and Auger recombination (τ_A, full line) [6]. The dotted lines represent the total lifetime according to:

$$1/\tau = 1/\tau_r + 1/\tau_A + 1/\tau_{SRH}, \quad (2)$$

where a Shockley–Read–Hall (τ_{SRH}) lifetime of ∞, 1000 and 100 ps is assumed (from the top to the bottom). Now τ-data that are carefully derived from τ_d-measurements are added. Results from three groups of samples, that differ with respect to the GaAs:C precursor material are analyzed. The data from one sample group (squares, TMG + AsH_3) exactly match the calculated theoretical density dependence limits,

without taking into account any extrinsic recombination. We consider this an excellent confirmation of the success of our attempts to minimize the influence of extrinsic effects, and can extract the coefficients for radiative and Auger recombination as $B = 0.5 \times 10^{-10}$ $cm^3\ s^{-1}$, $C = 4 \times 10^{-30}$ $cm^6\ s^{-1}$. The latter number very remarkably agrees with the $C = 6 \times 10^{-30}$ $cm^6\ s^{-1}$ published recently by Ahrenkiel et al. [12] for GaAs:C with $p_0 = 1 \times 10^{19}$ cm^{-3}. The results obtained from the other sample groups that are grown using $TMGa + AsH_3 + CBr_4$ (open circles) and $TMGa + TMAs$ (full triangles) as GaAs:C precursor indicate the presence of extrinsic effects. The assumption of additional Shockley–Read–Hall recombination allows to understand the results. Furthermore, it is possible to conclude that the use of $TMGa + AsH_3 + CBr_4$ leads to reduced extrinsic impacts to the recombination behavior compared to the use of $TMGa + TMAs$.

4. Summary

We present a study of the transient PL behavior of heavily doped GaAs:C at room temperature. This unusual measuring temperature was chosen in order to obtain lifetime data that allow conclusion with respect to HBT device properties. The room-temperature PL decay of many samples turns out to be governed by extrinsic effects.

We give experimental conditions that allow to minimize the impact of extrinsic effects. For the excitation density a compromise between the necessity to saturate traps and avoid stimulated emission is found. At room-temperature an excitation density of 10^{17} cm^{-3} per pulse meets this demand. Detection should be limited to a spectral window well above E_g. This allows to perform reliable PL decay time measurements providing τ-data for optimization of the metal–organic chemical vapor deposition. Thus we show how PL decay time measurements can be used as a tool for the estimation of expected HBT current gains on wafer scale immediately after epitaxial growth.

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