Title	Defect study of GaInP/GaAs based heterojunction bipolar transistor emitter layer
Author(s)	Cherkaoui, Karim; Murtagh, M. E.; Kelly, P. V.; Crean, Gabriel M.; Cassette, S.; Delage, S. L.; Bland, S. W.
Publication date	2002-01
Original citation	Cherkaoui, K., Murtagh, M. E., Kelly, P. V., Crean, G. M., Cassette, S., Delage, S. L. and Bland, S. W. (2002) 'Defect study of GaInP/GaAs based heterojunction bipolar transistor emitter layer', Journal of Applied Physics, 92(5), pp. 2803-2806.
Type of publication	Article (peer-reviewed)
Link to publisher's version	http://aip.scitation.org/doi/abs/10.1063/1.1500417 http://dx.doi.org/10.1063/1.1500417 Access to the full text of the published version may require a subscription.
Rights	**© 2002 American Institute of Physics, This article may be downloaded for personal use only. Any other use requires prior permission of the author and AIP Publishing. The following article appeared in Cherkaoui, K., Murtagh, M. E., Kelly, P. V., Crean, G. M., Cassette, S., Delage, S. L. and Bland, S. W. (2002) 'Defect study of GaInP/GaAs based heterojunction bipolar transistor emitter layer', Journal of Applied Physics, 92(5), pp. 2803-2806 and may be found at http://aip.scitation.org/doi/abs/10.1063/1.1500417**
Item downloaded from	http://hdl.handle.net/10468/4238

Defect study of GaInP/GaAs based heterojunction bipolar transistor emitter layer

K. Cherkaoui, M. E. Murtagh, P. V. Kelly, and G. M. CreanS. Cassette and S. L. DelageS. W. Bland

Citation: Journal of Applied Physics **92**, 2803 (2002); doi: 10.1063/1.1500417
View online: http://dx.doi.org/10.1063/1.1500417
View Table of Contents: http://aip.scitation.org/toc/jap/92/5
Published by the American Institute of Physics

JOURNAL OF APPLIED PHYSICS VOLUME 92, NUMBER 5 1 SEPTEMBER 2002

Defect study of GaInP/GaAs based heterojunction bipolar transistor emitter layer

K. Cherkaoui,[a] M. E. Murtagh, P. V. Kelly, and G. M. Crean
NMRC, Lee Maltings, Prospect Row, Cork, Ireland

S. Cassette and S. L. Delage
THALES Research and Technology-F, Domaine de Corbeville, 91404 Orsay Cedex, France

S. W. Bland
IQE (Europe) Limited, Pascal Close, Cypress Drive, St. Mellons, Cardiff, South Galmorgan CF3 0EG, Wales, United Kingdom

(Received 18 March 2002; accepted for publication 25 June 2002)

Defects in the emitter region of $Ga_{0.51}In_{0.49}P$/GaAs heterojunction bipolar transistors (HBTs) were investigated by means of deep-level transient spectroscopy. Both annealed (635 °C, 5 min) and as grown metalorganic chemical vapor deposition epitaxial wafers were investigated in this study, with an electron trap observed in the HBT emitter space-charge region from both wafers. The deep-level activation energy was determined to be 0.87 ± 0.05 eV below the conduction band, the capture cross section 3×10^{-14} cm^2 and the defect density of the order of 10^{14} cm^{-3}. This defect was also found to be localized at the emitter–base interface.
[DOI: 10.1063/1.1500417]

I. INTRODUCTION

GaAs based heterojunction bipolar transistors (HBTs) have attracted considerable interest due to the emerging wireless market. The GaInP/GaAs system is considered the technology of choice for various applications, indeed the $Ga_{0.51}In_{0.49}P$/GaAs emitter/base heterojunction offers an excellent band-gap lineup compared to other systems (e.g., GaAlAs/GaAs) with small conduction band offset, as well as a large valence band discontinuity[1] affording high emitter injection efficiency. Moreover, the very high etch rate selectivity between GaInP and GaAs simplifies device processing.[2]

However, there are still reliability issues that must be addressed in order to achieve better device performance and lifetime. Hydrogen (H) incorporation in the epilayers during metalorganic chemical vapor deposition (MOCVD) growth is one of the main reliability issues, acting as a compensating donor (H^+) for carbon (C) acceptors in the base layer. Hydrogen can also form CH and/or C_2H complexes passivating C acceptors. Furthermore, it has been shown that H in the base is responsible for direct current gain instabilities during device operation.[3–6]

In addition to the effect of hydrogen upon HBT reliability, deep levels present in the base–emitter depletion region affect device operation by increasing base leakage current. Electrons can recombine with holes at near midgap traps located in the depletion region, leading to an increase in the base leakage current. The nonradiative recombination energy can be converted into vibrational (phonon) energy, inducing point defect reactions such as diffusion that may in turn act as recombination centers.[7]

Several studies have investigated deep levels in InGaP material grown by various techniques. Defects were reported in InGaP layers grown by MOCVD,[8–11] vapor phase epitaxy,[12] liquid phase epitaxy,[13–15] metalorganic molecular-beam epitaxy,[16] as well as gas-source[17,18] and solid-source molecular-beam epitaxy.[19]

In this article, we report a deep-level transient spectroscopy (DLTS) study of the deep levels in the emitter layer of $Ga_{0.51}In_{0.49}P$/GaAs HBT transistors grown by MOCVD.

II. EXPERIMENTAL PROCEDURE

The DLTS experiments were carried out on fully processed MOCVD HBTs, as summarized in Table I, silicon and carbon were the *n*- and *p*-type dopants, respectively. The InGaP/GaAs HBTs were grown by MOCVD in an Aixtron 2400 multiwafer reactor. The epitaxial layers were grown at a pressure of 200 mbar using trimethygallium (TMG) and trimethylindium as the metalorganic sources, arsine and phosphine as the hydride sources, and disilane as the *n*-type dopant source. Carbon doping in the *p*-type GaAs base layer was achieved by intrinsic doping from the TMG source. Two wafers originating from the same batch were processed identically. Prior to the process, however, one of the wafers was annealed at 635 °C for 5 min, with GaAs proximity capping. Also for the isolation of the individual devices, wafers were boron implanted instead of proton irradiated to avoid any further H contamination. The contacts were Ti/Pt/Au for the base and AuGe/Ni/Au alloy for the collector. The emitter contact consisted of refractory metal (TiWSi/TiPtAu) in order to improve the thermal stability as well as to avoid metallurgical problems; the second layer enhances the conductivity. Large emitter area ($100 \times 100\ \mu m^2$) transistors were employed for capacitance measurements.

---

[a] Electronic mail: karimc@nmrc.ie

TABLE I. Summary of nominal MOCVD HBT device structure—layer thickness and doping levels. Both nonannealed and 635 °C (5 min) annealed structures were examined in this study.

Layer	Thickness (nm)	Doping level (cm^{-3})
n^+ InGaAs including graded layer	≈60	2×10^{19}
n^+ GaAs contact layer	200	2.1×10^{18}
n^+ GaInP interface layer	100	9.2×10^{17}
n GaInP ballast	250	9.4×10^{16}
n GaInP emitter	150	2.8×10^{17}
p^+ GaAs base	100	2.5×10^{19}
n GaAs collector	1000	2.2×10^{16}
n^+ GaAs subcollector	100	3.1×10^{18}
n^+ GaInP etch barrier	25	$>1\times10^{18}$
n^+ GaAs subcollector	800	3.5×10^{18}

The DLTS setup consists of a Boonton 72 capacitance meter and computer controlled data acquisition card. Capacitance transients were analyzed digitally using the boxcar DLTS method, and recorded over 80–450 K using a continuous flow liquid nitrogen cryostat. This DLTS study was carried out on the emitter–base junction with the collector potential kept floating.

III. RESULTS AND DISCUSSION

Capacitance voltage ($C-V$) measurement and DLTS were carried out on the p^+GaAs/n–InGaP junction of the transistors. The doping profile shown in Fig. 1, obtained using $C-V$ measurement, reveals dopant reactivation in the annealed emitter layer. We have also noticed similar dopant reactivation for the annealed collector region. As hydrogen is expected to be in the structures due to the MOCVD growth technique, such dopant reactivation, is likely due to hydrogen outdiffusion, following 635 °C for 5 min.[6]

Figure 2 presents the DLTS spectrum of the emitter–base junction, measured with a reverse bias of 2 V and pulse height of 1 V with 5 ms duration. A single large peak dominates the spectrum at high temperature, above 400 K and is consistent with a very deep electron trap in the emitter space-charge region. The activation energy (E_T) extracted from the corresponding Arrhenius plot was $0.87\pm0.05\,\mathrm{eV}$, with a capture cross section $\sigma=3\times10^{-14}\,\mathrm{cm}^2$. The amplitude of the DLTS signal yielded a defect density of the order of $10^{14}\,\mathrm{cm}^{-3}$. This defect was detected in all transistors from both annealed and nonannealed (as-grown) wafers, thus it is not induced by the anneal process.

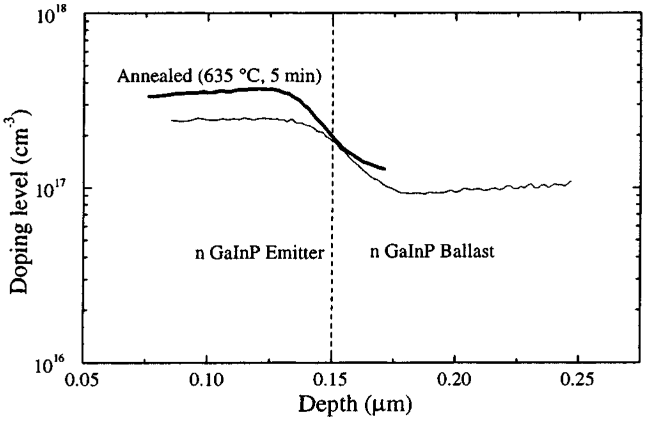

FIG. 1. Doping profile deduced from $C-V$ measurement for both annealed 635 °C for 5 min (bold line) and nonannealed samples. The dopant reactivation observed is consistent with H outdiffusion.

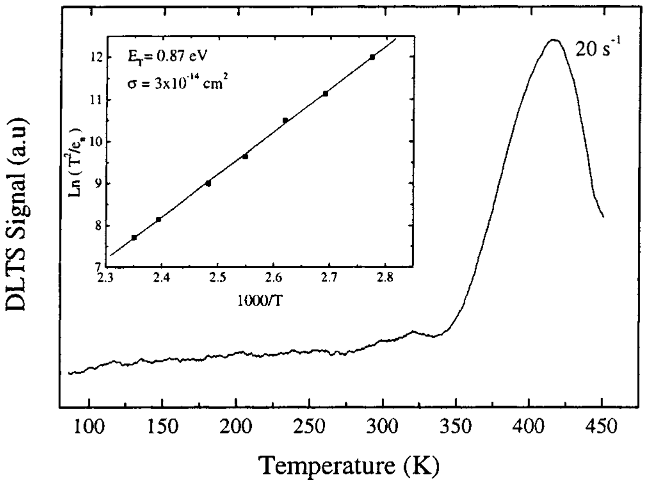

FIG. 2. DLTS spectrum (nonannealed transistor) obtained with reverse bias voltage $V_r=2$ V and pulse amplitude $V_p=1$ V, emission rate window 20 s^{-1}, and pulse duration $t_p=5$ ms. The corresponding Arrhenius plot is shown in the inset.

The DLTS peak amplitude was observed to vary strongly with reverse bias voltage. Figure 3 presents three DLTS spectra obtained for various reverse bias voltages, 3 V to 1 V, at constant filling pulse amplitude, 1 V. The DLTS signal increased with decreasing reverse bias, that is when probing the region closer to the emitter/base interface. Conversely, the DLTS signal is totally extinguished when probing far from the interface, implying the deep level to thus correspond to a defect localized at the emitter–base interface. Note that the small temperature lowering observed for the low bias conditions is unlikely to be attributed to electric-field enhanced effects, given the constant pulse amplitude

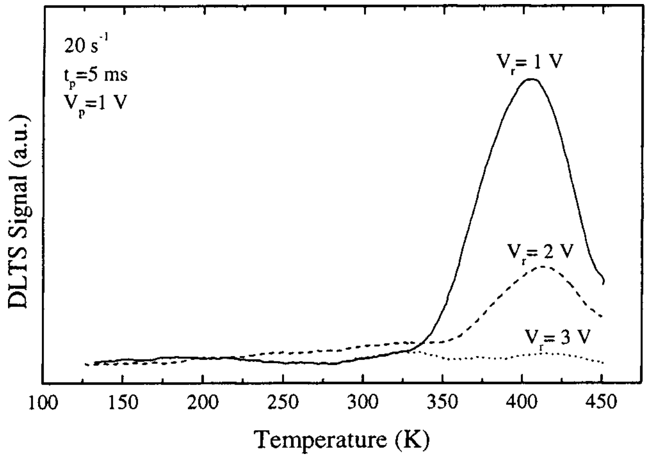

FIG. 3. DLTS spectra obtained at different reverse bias voltages (V_r) with the pulse amplitude kept constant, 1 V. Solid line $V_r=1$ V, dashed line $V_r=2$ V, dotted line $V_r=3$ V, with emission rate window 20 s^{-1}, and pulse duration $t_p=5$ ms.

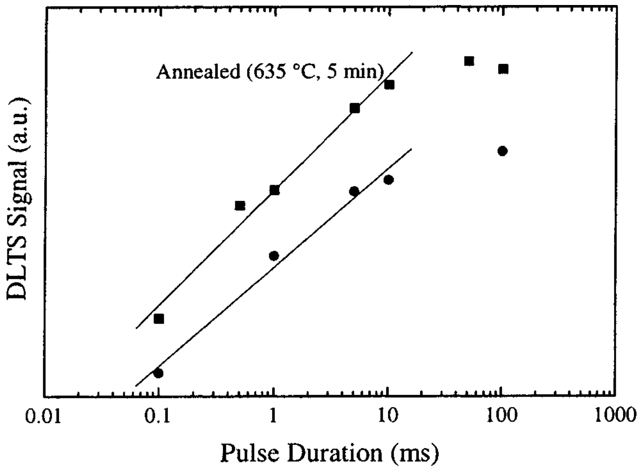

FIG. 4. Logarithmic dependence of the DLTS signal with filling pulse duration for both nonannealed (●) and annealed (■) HBTs. Note the onset of saturation above 10 ms.

measurement conditions. A possible origin for such a shift may be band gap lowering toward the InGaP/GaAs interface.

To investigate more about the 0.87 eV level, several DLTS spectra were recorded with the same experimental conditions as presented in Fig. 4, but with varied filling pulse duration, 0.1–100 ms. The dependence of the DLTS peak amplitude upon the pulse duration gives significant information on the defect capture kinetics. For an ideal point defect, the DLTS signal amplitude varies exponentially with pulse duration.[20] However, the DLTS signal for the 0.87 eV level exhibits a clear logarithmic behavior, saturating after long filling pulses >10 ms, Fig. 4. The slight DLTS signal increase observed following 635 °C for 5 min anneal may arise from hydrogen trap depassivation effects.

The logarithmic dependence of the DLTS signal with pulse duration has already been observed in plastically deformed silicon and III–V materials.[20,21] Such behavior was attributed to point defects located in the vicinity of, or adjacent to, lattice dislocations. In this model, the logarithmic dependence results from a repulsive Coulomb potential, depending upon the occupation of the extended defect, itself a function of the filling pulse duration. Moreover, according to this model, the defect is neutral before capture and negatively charged after, thus implying an acceptor defect.

Feng *et al.*[8] observed by DLTS a deep level with an activation energy of about 0.9 eV in nonintentionally doped MOCVD $In_{0.49}Ga_{0.51}P$ ($\sim 1\ \mu$m) epilayers.[8] Interestingly, this level was also located close to the n^+ GaAs–substrate interface. However, the DLTS peak corresponding to the 0.9 eV was very broad and consisted of a doublet structure. The deep level that we have detected in this study shows a broad DLTS peak, however, it was not possible to distinguish any other components, either by varying the bias or the duration and amplitude of the filling pulse. A DLTS dependence upon pulse duration was also reported by Feng *et al.*,[8] however the nonsaturation of the signal was attributed to a lack of free carriers. In our case, the free carrier concentration is at least two orders of magnitude higher than the trap density (10^{14} cm^{-3}). Therefore, the logarithmic behavior that we observed is not due to a lack of free carriers. Considering the similarities between the deep level detected in this study and that reported by Feng *et al.*[8] (activation energy and interface localization), we can reasonably, assume, therefore that both levels originate from the same defect.

Several authors also observed deep levels featuring activation energies within the same energy range as the deep level concerned in this study. A deep electron trap at $E_c - 0.85$ eV was reported in MOCVD grown $In_xGa_{1-x}P$,[9] and detected only with the In composition $x > 0.532$. This defect was uniformly distributed in the InGaP layer. It was concluded that this level was not a lattice-mismatch induced trap but probably a native defect associated with the stoichiometry of In or Ga. Moreover, Paloura *et al.*[12] observed a very broad DLTS peak corresponding to a deep level in the range of 0.7–0.9 eV in undoped metalorganic vapor phase epitaxy $Ga_{0.51}In_{0.49}P$ layers. This deep center was also detected in moderately Se doped layers, but was extinguished at Se doping levels higher than 10^{17} cm^{-3}. This level did not show any bias dependence. The large peak broadening was attributed to microscale variations of the alloy composition.

The origin of the single trap observed in this study, therefore, is not clearly identified. However, assuming the same defect level as observed by Feng *et al.*,[8] we can, therefore, exclude the possibility that it is induced by the HBT fabrication process. Note that the silicon dopant can also be eliminated as a possible origin of this defect because it was also detected in nonintentionally doped epilayers.[8] Although these MOCVD structures contain large concentrations of hydrogen, it is very unlikely that this defect is induced by hydrogen because it was detected with similar densities in both annealed and nonannealed samples.

Considering this defect localization at the InGaP/GaAs interface and its logarithmic capture kinetics, we suspect that it is related to an extendedlike deep level in the InGaP layer. This extendedlike behavior is due to a high localization of the deep levels. Indeed, these unusual capture kinetics result from a strong interaction between the emitting centers. This only indicates that the defects are closely spaced in the lattice, the exact nature of this defect and the origin of its extendedlike behavior are still uncertain. Therefore, such extendedlike behavior can possibly be associated with both point defects, assuming sufficient localization such that adjacent defects interact, or true extended defects.

Finally, although it is commonly accepted that the recombination rate at the emitter–base interface of InGaP/GaAs HBTs is very low compared to AlGaAs/GaAs HBTs, the presence of such deep levels at the InGaP/GaAs interface and its near midgap energy position ($In_{0.49}Ga_{0.51}P$ band gap $\sim$1.9 eV), might lead to an increase in nonradiative recombination, thus resulting in an increase in base leakage current. This may not affect the device operation at the early stages, however, it could be responsible for long-term HBT degradation as described by Henderson.[7] It should be noted however that lifetime results on HBT devices made from epitaxial layers produced at the same time using the same growth process show excellent long-term reliability, with no failures after more than 6000 h at a current density of 40 kAcm^2 and junction temperature of 296 °C.[22]

IV. CONCLUSION

To conclude, a deep electron trap has been detected in this DLTS study of MOCVD InGaP/GaAs based HBT devices. A deep level with an activation energy around 0.87 eV has been detected in the emitter layer of fully processed HBTs. This deep level was observed in both annealed and nonannealed samples. We have also shown that this center is located at the InGaP/GaAs interface and exhibits an unusual logarithmic capture mechanism.

ACKNOWLEDGMENTS

This work was supported by the European Union—HERO’S Project, EU BRITE program-BRPR-CT98-0789.

[1] M. J. Monday and H. Kroemer, IEEE Electron Device Lett. **6**, 175 (1985).
[2] F. Ren, C. R. Abernathy, S. J. Pearton, L. W. Yang, S. T. Fu, Solid-State Electron. **38**, 1635 (1995).
[3] F. Ren, C. R. Abernathy, S. N. G. Chu, J. R. Lothian, and S. J. Pearton, Solid-State Electron. **38**, 1137 (1995).
[4] H. Fushimi and K. Wada, IEEE Trans. Electron Devices **44**, 1996 (1997).
[5] A. Kawano, K. Imanishi, T. Tomioka, T. Iwai, K. Ishii, and Y. Yamaguchi, Solid-State Electron. **42**, 2057 (1998).
[6] S. Cassette, S. L. Delage, E. Chartier, D. Floriot, M. A. Poisson, J. C. Garcia, C. Grattepain, J. Mimila Arroyo, R. Plana, and S. W. Bland, Mater. Sci. Eng., B **80**, 279 (2001).
[7] T. Henderson, Microelectron. Reliab. **39**, 1033 (1999).
[8] S. L. Feng, J. C. Bourgoin, F. Omnes, and M. Razeghi, Appl. Phys. Lett. **59**, 941 (1991).
[9] Z. C. Huang, B. Yang, H. K. Chen, and J. C. Chen, J. Vac. Sci. Technol. B **13**, 2049 (1995).
[10] A. Khan, M. Yamaguchi, T. Takamoto, N. de Angelis, and J. C. Bourgoin, J. Cryst. Growth **210**, 264 (2000).
[11] J. Krynicki, M. A. Zaidi, M. Zazoui, J. C. Bourgoin, M. DiForte-Poisson, C. Brylinski, S. L. Delage, and H. Blanck, J. Appl. Phys. **74**, 260 (1993).
[12] E. C. Paloura, A. Ginoudi, G. Kiriakidis, N. Frangis, F. Scholz, M. Moser, and A. Christou, Appl. Phys. Lett. **60**, 2749 (1992).
[13] J. B. Lee, S. D. Kwon, I. Kim, Y. H. Cho, and B. D. Choe, J. Appl. Phys. **71**, 5016 (1992).
[14] M. G. Kim, S. D. Kwon, C. H. Kim, J. B. Lee, B. D. Choe, and H. Lim, Appl. Phys. Lett. **63**, 1366 (1993).
[15] S. D. Kwon, H. K. Kwon, B. D. Choe, and H. Lim, Appl. Phys. Lett. **67**, 2533 (1995).
[16] E. C. Paloura, A. Ginoudi, G. Kiriakidis, and A. Christou, Appl. Phys. Lett. **59**, 3127 (1991).
[17] C. Besikci and Y. Civan, Thin Solid Films **338**, 213 (1999).
[18] H. S. Kim, M. J. Hafish, G. A. Patrizi, A. Nanda, T. J. Vogt, L. M. Woods, and G. Y. Robinson, J. Appl. Phys. **74**, 1431 (1993).
[19] S. F. Yoon, P. Y. Lui, and H. Q. Zheng, J. Cryst. Growth **203**, 31 (1999).
[20] P. Omling, E. R. Weber, and L. Montelius, H. Alexander, and H. Michel, Phys. Rev. B **32**, 6571 (1985).
[21] S. A. Ringel, Solid-State Electron. **41**, 359 (1997).
[22] C. Sydlo, B. Motter, H. Ganis, H. L. Hartnagel, V. Krozer, S. L. Delage, S. Cassette, E. Chartier, D. Floriot, and S. Bland, Microelectron. Reliab. **41**, 1567 (2001).