Materials for GaInP/GaAs HBT's performed within the GAMMA project

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ABSTRACT

This paper describes the development of a European source of GaInP HBT epitaxial wafers within the ESPRIT GAMMA (GaAs Materials for Microwave Applications) project. The GAMMA project started in May 1996 and was completed at the end of May 1998. At the start of the project there was no credible source for GaInP HBT epitaxial wafers within Europe, however by the end of the project Epitaxial Products International Ltd (EPI) had established a world-class capability for the supply of 3" and 4" diameter epitaxial wafers.

INTRODUCTION

The GAMMA (GaAs Materials for Microwave Applications) project started in May 1996 and finished at the end of May 1998. The project was supported under the ESPRIT scheme and its objective was to strengthen the European infrastructure in GaAs materials in order to support the growing end-user requirement. The project comprised 3 workpackages on (i) 4" semi-insulating GaAs substrates for ion-implantation, (ii) 4" Pseudomorphic HEMTs and (iii) Multiwafer MOVPE GaInP HBTs. The other partners were the prime contractors LEP SAS – Philips Microwave Limeil (France) along with Freiberger Compound Materials (Germany), Picogiga (France), Siemens Aktiengesellschaft (Germany), United Monolithic Semiconductors SAS (France), United Monolithic Semiconductors GmbH (Germany), Thomson-CSF LCR (France), Marconi Materials Technology (UK), Fraunhofer Institute – IAF (Germany), Ferdinand-Braun-Institute (Germany) and FORTH (Crete).

The overall aim of the 'Multiwafer MOVPE GaInP HBT' workpackage was to establish Epitaxial Products International Ltd (EPI) as a qualified source of high quality GaInP HBT epitaxial wafers to the European manufacturing industry. The workpackage comprised two subtasks; the first subtask was on "Specification, characterisation and optimisation of GaInP HBT structures" and the second subtask was on "GaInP HBT device and circuit fabrication". The overall workpackage involved 5 partners, namely EPI, IAF, FBH, Thomson, UMS and MMT. EPI were tasked with the development of the multiwafer epitaxial growth technology for GaInP HBT structures with assistance from IAF and with rapid turnaround device feedback plus materials characterisation by FBH and Thomson-LCR. The industrial users, UMS and MMT, took the wafers produced by EPI and processed them in their production line alongside standard production wafers procured from other sources world-wide in order to provide the necessary benchmarking.

The interactions between the partners is shown schematically in figure 1. FBH and Thomson-CSF (and to some extent MMT) provided rapid device level and materials level feedback to EPI and IAF. MMT and UMS provided device/circuit level feedback using their full production processes. Comparisons between IAF and EPI wafers helped to accelerate the development activity.

EXPERIMENTAL APPROACH

An important aspect of the project implementation plan was to regularly benchmark the epitaxial wafers being developed by EPI against commercially available material. Such benchmarking was achieved by the end-users in a true production environment. It should be noted that at the outset of the project, EPI was not in a position to supply high quality GaInP HBT epitaxial wafers. At this time the only viable source of GaInP HBT wafers was Epitronics in the US, with Kopin a major supplier of AlGaAs and in the process of developing a GaInP HBT product. Therefore the first stage was to establish the epitaxial layer specifications from each of the end users and to determine the baseline position. The baseline was monitored by fabricating devices from epitaxial wafers supplied by EPI using standard growth processes and comparing these with the state-of-the-art material.

It was expected that the first layers would fall short of the required standard and therefore the next stage would be to carefully evaluate the materials characterisation and device results to identify the various development steps required to achieve high quality epitaxial wafers to these precise specifications. The final stage would involve detailed optimisation of the quality of the GaInP HBT wafers in terms of absolute device/circuit performance, uniformity of materials and device parameters, reproducibility of device/circuit performance from wafer-to-wafer and run-to-run, and reliability.

The initial benchmarking activity identified a large discrepancy in performance between epitaxial wafers grown using the baseline EPI and IAF growth processes and the commercial state of the art. Figure 2 shows a comparison of the baseline results with published data from Kopin (1) for AlGaAs and GaInP which represents the commercial state of the art. In this figure, current gain is taken as the key device level parameter and is plotted as a function of base sheet resistance. Approximately equivalent levels of performance are represented by the slope of the line in figure 2 which follows the relationship $\beta \propto (Rsh)^2$, assuming that recombination in the base layer dominates. Essentially the baseline results were around a factor of 10 worse than the state-of-the-art.

The project then embarked upon a systematic programme of epitaxial growth optimisation in order to achieve an equivalent level of performance as the competitive material and hence enable EPI to become a viable volume supplier of GaInP HBT epitaxial wafers. Optimisation focussed on the quality of the carbon doped base layer and the quality of the critical GaAs-GaInP base-emitter interface. Work was also undertaken to optimise the n^+ InGaAs contact layer to achieve high doping levels, high indium compositions and smooth morphology.

MATERIALS OPTIMISATION

The growth work was performed on 2 different AIXTRON planetary multiwafer reactors; an AIX2000 multiwafer reactor which is capable of handling up to 5x3" diameter wafers, and the larger scale AIX2400 multiwafer reactor which is capable of handling up to 4" diameter wafers (8x3" or 5x4"). Growth was performed using conventional precursors, i.e. TMG, TMI, AsH_3, PH_3 and Si_2H_6.

During the course of the project, EPI has investigated optimisation of the GaAs:C base layer growth technology in order to achieve accurate control of the base doping level and thickness (i.e. base sheet resistance), good doping level uniformity across 3" and 4" diameter wafers and high quality material free from hydrogen contamination. High quality GaAs:C material with good minority carrier lifetimes is critical for realising high performance devices. Statistical experimental design methods were employed to investigate the parameter space for intrinsic carbon doping using TMG and AsH_3. Response surfaces illustrated the interplay between the various key growth parameters, i.e. V/III ratio and growth temperature.

It was found that the doping level increased systematically as the growth temperature was reduced but was a more complex function of V/III ratio. Initially as the V/III ratio was reduced the doping increased, however, at very low V/III ratios the doping actually reduced. The morphology in the low V/III and high temperature regime was also degraded. Therefore it was important to avoid this growth regime. The growth rate (thickness) reduced as the temperature was reduced and became dependent on the V/III ratio at lower temperatures. The intrinsic doping design spanned the range $6x10^{18}$ cm^{-3} to $6x10^{19}$ cm^{-3} and enabled optimum conditions to be determined for the project requirement of between $3\text{-}4x10^{19}$ cm^{-3}. Many base doping experiments were performed and from the data collected it was possible to establish an empirical relationship between p-doping level p (cm^{-3}), sheet resistance R_{sh} (Ω/sq) and layer thickness d (Å). The equation is $p = 8.1x10^{24}/d.R_{sh}$. For example, a doping level of $5x10^{19}$ cm^{-3} and a base thickness of 800 Å gives a sheet resistance of 202.5 Ω/sq.

Hydrogen passivation of the GaAs:C base layer must be minimised to achieve high performance devices which are stable and reliable. Therefore the growth conditions were also optimised to reduce the hydrogen content. Figure 3 shows a SIMS profile for a typical HBT structure, which indicates that the hydrogen content is below the detection limit ($<1x10^{18}$ cm^{-3}). This level compares favourably with commercial material tested within the project, which showed hydrogen levels up to $2x10^{19}$ cm^{-3}.

Highly doped layers of n^+-InGaAs are required in order to achieve non-alloyed ohmic contacts to the emitter layer. The key issues in the growth of such a layer are the need to accommodate the large lattice mismatch of around 3.5% (for $In_{0.5}Ga_{0.5}As$), achieve very high n-type doping levels (around $2x10^{19}$ cm^{-3}) while avoiding 3 dimensional growth (i.e. maintaining a smooth surface morphology). After some experimentation EPI was able to establish optimum conditions which showed extremely smooth surfaces as measured by AFM (RMS roughness around 1-2 nm), very low contact resistivities (around $1\text{-}2x10^{-7}$ $\Omega.cm^2$) and extremely good stability/reliability. The AFM results are compared with commercially available material in figure 4.

DEVICE STRUCTURE OPTIMISATION

Optimisation of the individual layers is only one aspect of the final goal, which is optimisation of the full HBT structure. Putting the individual layers together successfully, especially optimising the critical base-emitter interfacial quality, required a number of growth process iterations. Each iteration required rapid feedback on material parameters and device parameters. A key strength of the project was the availability of high quality materials and device feedback from FBH and Thomson-CSF on a rapid turn-around basis. Without such rapid feedback the project timescales would not have been achieved.

Optimisation of the base and base-emitter interface quality was achieved relatively quickly within the project and the current gain was improved to a level consistent with the Kopin data. Figure 5 shows representative results obtained over the life of the project for GaInP HBTs. Once the basic device performance had been established, work was performed to optimise other critical parameters such as uniformity of the base sheet resistance (carbon doping) and of the current gain. Figure 6 shows a uniformity map for a 3" diameter wafer which has a mean value of 247 ohm/sq and a 1σ standard deviation of 1.9 ohm/sq ($\pm$ 0.8%), as measured by MMT. FBH also measured excellent uniformity with a base sheet resistance of 199 $\pm$ 2 ohm/sq ($\pm$1%) and a maximum current gain uniformity of 97 $\pm$ 2.4 ($\pm$2%). A typical Gummel plot and IV characteristic for this wafer is shown in figure 7. Optimisation and control of the carbon doping was also investigated in order to achieve a wide range of base sheet resistance values to satisfy the differing requirements of the end users.

Excellent RF results were also achieved. MMT reported RF measurements on small area (3 x 20 μm^2) test devices which gave f_T and f_{max} values of around 42 GHz and 46 GHz respectively. Measurements on static divide-by-two circuits showed a high yield of working circuits, with divider operation typically up to 12 GHz. Of the 44 sites on the wafer, 39 (89%) gave working circuits. A broadband Darlington amplifier also showed a high yield of working circuits, with 104 circuits out of a total of 122 operating (85%).

Much of the project work was concerned with optimisation on 3" diameter wafers since this was the primary end-user requirement. Toward the latter stages of the project, EPI successfully developed a 4" GaInP HBT technology. This was achieved through technology transfer from the AIX2000 system to the larger AIX2400 system. The larger system can handle up to 5x4" or 8x3" substrates per run compared with the AIX2000, which can only handle up to 5x3" substrates per run.

The technology transfer process was completely successful. The uniformity and performance on the 4" wafers using the larger machine was equivalent to that obtained for 3" wafers on the smaller machine. Processing of the 4" wafers was performed by FBH, who were the only partner able to process 4" wafers at that time. FBH reported a base sheet resistance of 191 $\pm$ 1.7 ($\pm$ 0.9%) and a maximum current gain of 88 $\pm$ 3.6 ($\pm$4%).

CONCLUSIONS

The project has been successful in its primary aim which has been to establish an European source of GaInP HBT epitaxial wafers which is competitive with other commercial sources world-wide. The objective has been achieved through a programme which involved close interaction between the partners. One of the critical aspects of the progress was the availability of rapid feedback from FBH and Thomson-LCR to the epitaxial growers, EPI and IAF. This feedback covered the equally important areas of advanced materials characterisation and device level results. Based on this feedback it was possible to focus the development work and address those key issues which were affecting the device performance. Consequently the epitaxial growth was concentrated on the GaAs/GaInP base-emitter interface and the base doping level control/reproducibility.

The final results are in good agreement with the materials and device targets, which were set at the beginning of the contract. The device results are comparable with the state-of-the-art and in a number of respects they exceed the state-of-the-art. For example, the uniformity on wafer is extremely good. A value of ±1% uniformity for base sheet resistance over 3" and 4" diameter wafers is regularly achieved which is significantly better than can be offered by other suppliers. Similarly the current gain uniformity is excellent and exceeds results achieved for commercial material. The hydrogen content of the base layer is significantly lower for EPI material than for both of the main competitors which is reflected in excellent short term current gain stability. Finally the technology which has been developed for the n^+ InGaAs cap layer produces very smooth surface morphologies and is demonstrating excellent stability under elevated temperature anneals.

The end users (MMT and UMS) have been able to evaluate epitaxial layers from EPI during the project and build confidence in the product. This has resulted in the first order for commercial material being placed by MMT toward the end of the project. UMS has stated that it also intends to buy material from EPI to evaluate reliability, particularly now that the stability of the n^+ InGaAs cap layer and GaAs base layer has been demonstrated. Thomson-CSF/LCR has already bought optimised wafers from EPI to test them in RF process regarding reliability/stability. The importance of understanding and optimising GaInP HBT reliability is being addressed through a new BRITE/EURAM project (HERO'S n° BE 97-5068) which involves three of the existing GAMMA partners.

ACKNOWLEDGEMENTS

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REFERENCES

(1) http://www.kopin.com

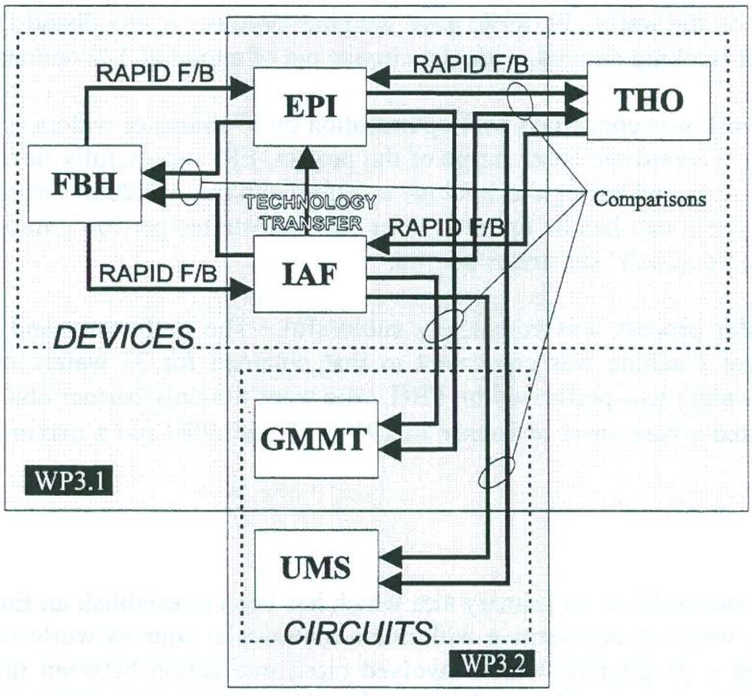

Figure 1. Schematic representation of the GAMMA GaInP HBT activity

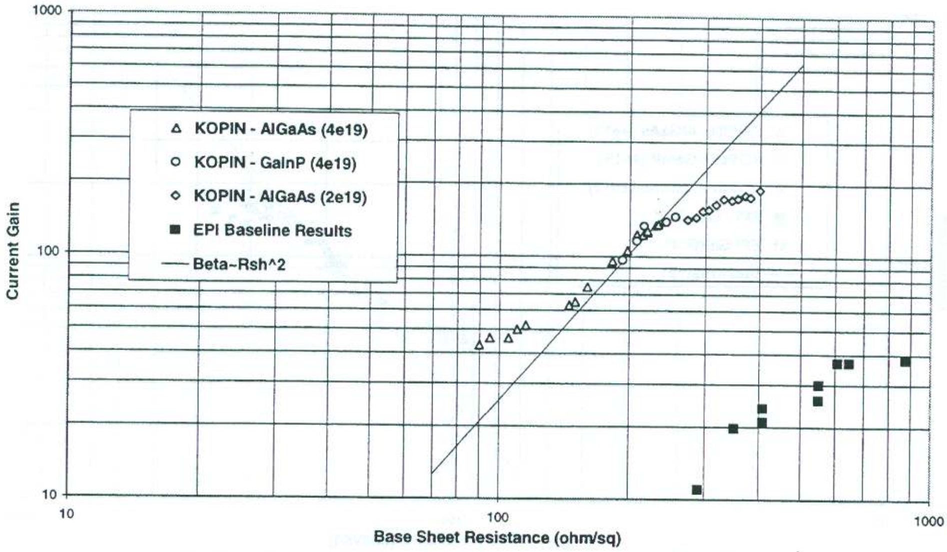

Figure 2. Comparison between results reported by Kopin and the baseline material produced by EPI.

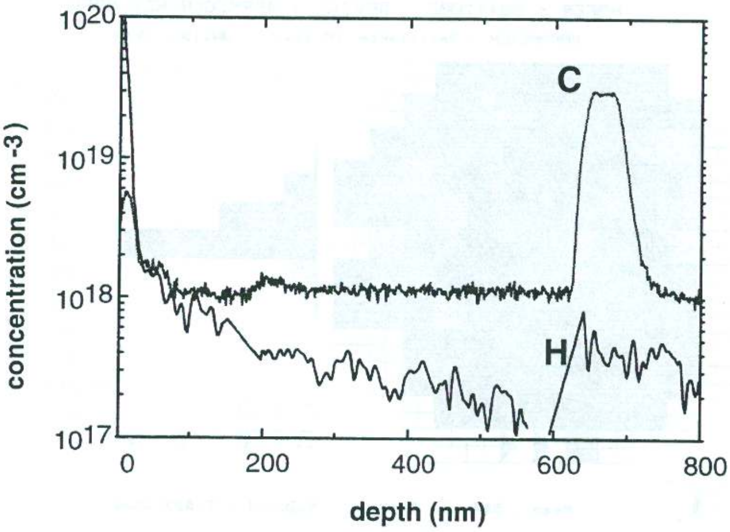

Figure 3. SIMS profile for C-doped GaAs base layer showing low hydrogen contamination. Note that the SIMS background level is around $1x10^{18}$ cm^{-3}.
(Data provided by FBH)

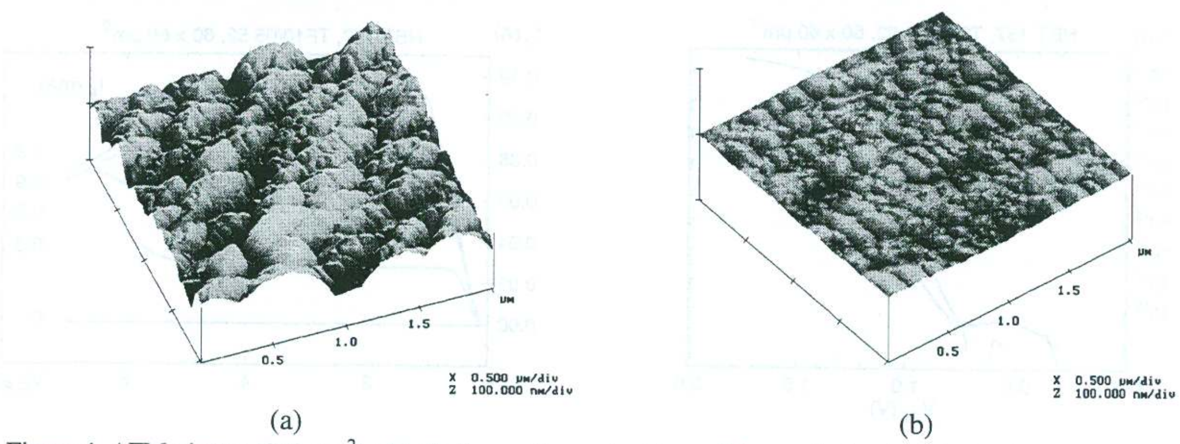

Figure 4. AFM picture (2x2 μm^2) of InGaAs emitter contact layer. The vertical axis scale is 100 nm per division.
(a) commercially available HBT wafer, and (b) EPI wafer.
(Data provided by FBH)

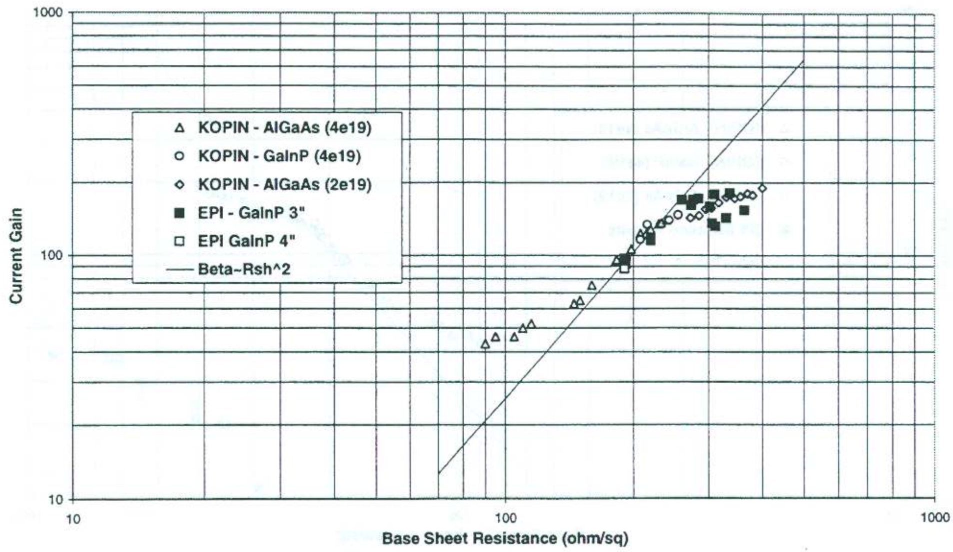

Figure 5. Comparison between results reported by Kopin and those achieved on EPI material at end of project

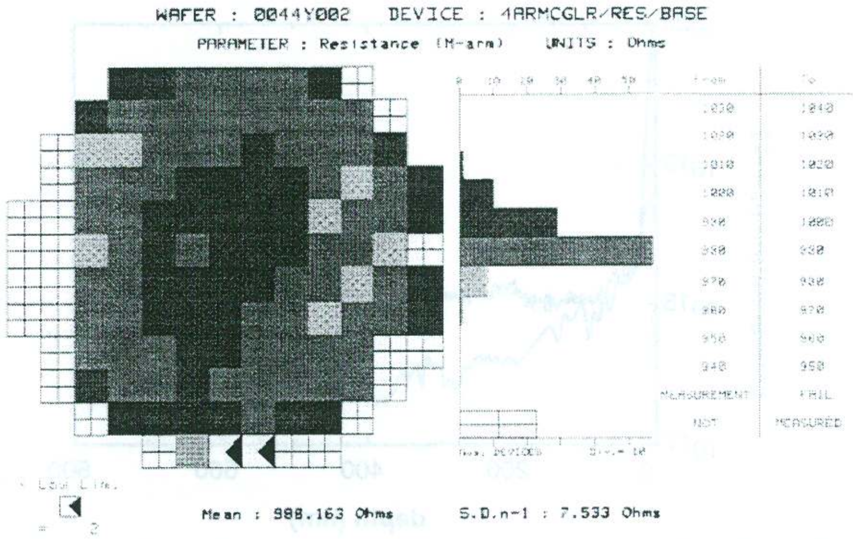

Figure 6. Sheet resistance map (resistor test structure) showing excellent uniformity of ± 0.8% on a 3" diameter wafer
(Data provided by MMT)

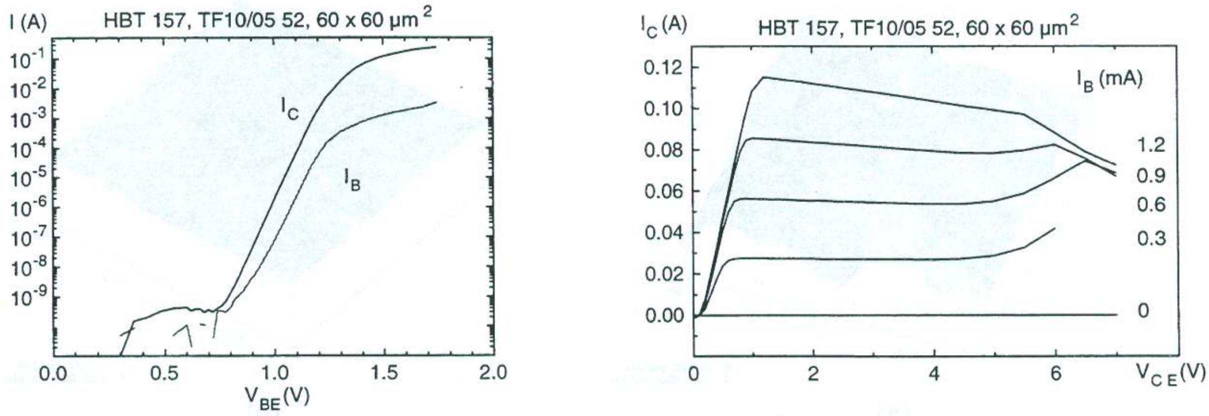

Figure 7. Typical Gummel plot and IV characteristics for GaInP HBT on 3" wafer. Base-collector and emitter-base ideality factors are 1.06 and 1.14 respectively.
(Data provided by FBH).