Material quality and uniformity issues of MOVPE-grown GaInP/GaAs HBTs

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Abstract

This extended abstract provides correlations between epitaxial growth parameters of HBTs and device performance. Optimizing the single p-GaAs layer quality leads to the highest DC current gain obtained but at the expense of non-ideal uniformity of the base sheet resistance. Near perfectly uniform base sheet layer on 4 inch wafers is achieved by changing the parameters for the intrinsic carbon doping but the HBT current gain decreases. The consequences of this compromise for HBT performance and reliability are discussed. State-of-the-art HBT single devices (3x30 µm^2) as well as multifinger power cells were fabricated.

INTRODUCTION

The great potential of GaAs-based heterojunction bipolar transistors (HBTs) for power applications in mobile communication is widely recognized. The further advancement of HBT devices crucially depends on the availability of a mature growth and processing technology. Recently, high-volume production of epitaxial HBT-wafers is achieved by commercial suppliers [1]. Here, metalorganic vapour phase epitaxy (MOVPE) has shown its capability to combine the required high throughput and high material quality. In this paper we report on optimization of MOVPE growth technology for highly uniform growth of high quality GaInP/GaAs HBT structures on 4-inch GaAs substrates.

EXPERIMENTAL

HBT wafers are grown in an Aixtron AIX2400 Planetary^{TM} MOVPE reactor. The layer structures mainly consist of a 700 nm GaAs subcollector layer ($n=5*10^{18}cm^{-3}$), a 700 nm GaAs collector layer ($n = 1.5*10^{16}$ cm^{-3}), a 120 nm GaAs base layer ($p = 3*10^{19}$ cm^{-3}), a 40 nm $Ga_{0.51}In_{0.49}P$ emitter layer ($n = 4.5*10^{17}$ cm^{-3}), GaAs and InGaAs contact layers. Si and C are used for the n-type and p-type doping.

In order to achieve the required high p-doping levels in the base layers the so-called intrinsic carbon doping [2] was applied during the epitaxial growth. This method utilizes carbon groups coming from pyrolysis of the organometallic Ga-precursor trimethylgallium (TMGa) as p-dopants. However, for high carbon uptake into GaAs very low flow of the As-precursor arsine (AsH_3) has to be used due to its impact as hydrogen supplier to the surface and thus as carbon remover. Therefore, a tight balance of growth parameters is required to obtain a homogeneous and reproducible base layer growth.

Due to the narrow parameter region given by the intrinsic carbon doping already small variations of growth conditions lead to significant changes of p-GaAs layer properties. Here, two different growth conditions A and B were used. Growth parameters A are optimized for the best p-GaAs single layer quality as checked by majority carrier mobility, X-ray peak width and surface morphology. Condition B represents a small deviation from this optimum toward better intrinsic doping homogeneity on a 4 inch wafer.

Our HBT process technology is based on a three-mesa approach in order to access the base and the collector layers and to provide device isolation. The lateral device definition is based on a selective dry-etching process as published in [3]. $WSiN_x$/Ti/Pt/Au, Ti/Pt/Au and Ni/Ge/Au/Ni/Au metal systems are used for the emitter, base and collector contacts, respectively. Interconnections are made by Ti/Pt/Au metal and emitter thermal shunts are formed by a 20 µm thick electroplated Au layer [3]. HBT single devices with emitter areas of 60x60 µm^2 and 3x30 µm^2 as well as power cells with up to 10 emitter fingers and total emitter area of 10x3x30 µm^2 are fabricated. DC measurements are performed using a commercial wafer mapping system. The microwave performance is characterized by RF and active load-pull measurements at 2 GHz and $V_{ce} = 3$ V.

RESULTS

One crucial issue for HBT applications is the homogeneity of the base layer. Fig. 1 shows the uniformity of the base sheet resistance R_{sb} for the HBT-base layers grown under conditions A and B. Base layer A exhibits a strong increase of R_{sb} up to 20% from the center toward the periphery of the wafer (standard deviation $\sigma = 3.5\%$). Base layer B shows nearly perfect homogeneity of R_{sb} with an increase well below 5% in the edge region of the wafer only (standard deviation $\sigma = 0.5\%$).

The HBT performance of the differently uniform HBT structures was compared by DC measurements. Fig. 2 shows the DC current gain for large area 60x60 μm^2 as well as for small 3x30 μm^2 HBT devices produced on wafers with the base layer A or B. In both cases the current gain traces the R_{sb} uniformity leading to higher current gain for higher base sheet resistance. The higher current gain of the small HBTs as compared with the large area devices demonstrates the efficient GaInP ledge technology that has been applied in the power cell process only. The presence of the ledge leads to a significant reduction of extrinsic base recombination currents. The main difference between the wafers is correlated with the different base growth conditions: the uniform base layer B leads to a 15% smaller current gain. As the current gain strongly depends on the minority carrier lifetime, a smaller electron lifetime in the base layer grown at condition B can be expected. Thus, this result indicates that a less defect-free GaAs:C layer is obtained after changing the growth parameters toward better layer homogeneity.

As a figure-of-merit for the DC HBT performance the ratio of current gain to base sheet resistance is commonly used [4]. Fig. 3 shows the β/R_{sb}-ratio in dependence on the different growth conditions A and B for the large area HBTs. Growth condition A results in a high β/R_{sb}-value of more than 0.52 indicating that the optimization of the base growth parameters for the best single GaAs:C layer quality regardless their resistance homogeneity indeed gives the best HBT performance. Using growth condition B the β/R_{sb}-value decreases to 0.48. However, this lower β/R_{sb}-value is in good agreement with published data for state-of-the-art HBT devices [4]. Thus, optimizing the growth conditions toward the best homogeneity of base sheet resistance does not dramatically compromise the HBT performance.

The state-of-the-art HBT quality was confirmed by RF measurements. The corner frequencies f_T / f_{max} are 37 GHz / 55 GHz for 8x3x30 μm^2 power cells, respectively. Load pull measurements gave output power values of 20 dBm for single HBTs and 30 dBm for power cells (V_{CE}=3V, 2 GHz).

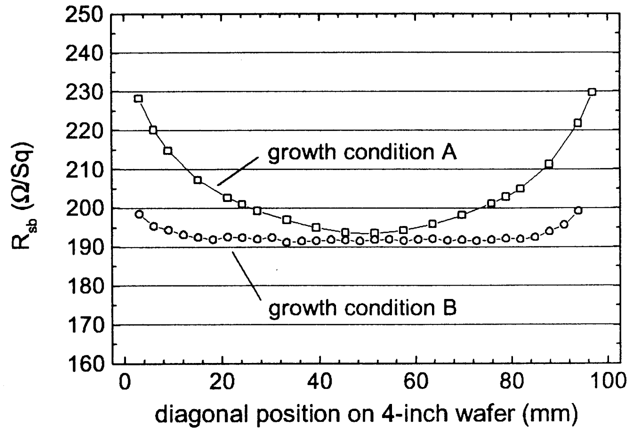

Fig. 1 Homogeneity of base sheet resistance R_{sb} on 4-inch HBT wafers grown under different conditions A and B.

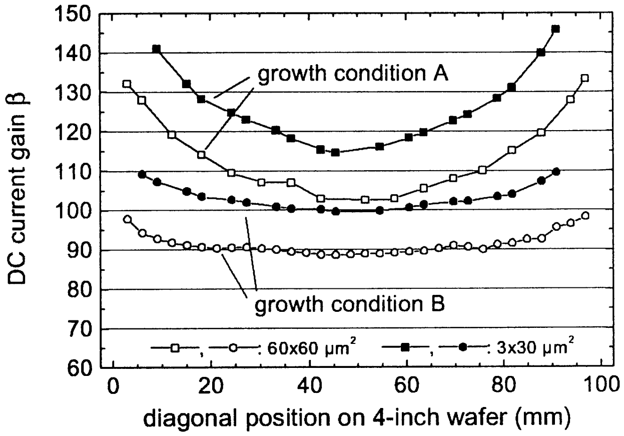

Fig. 2 Current gain uniformity for large area 60x60 μm^2 and small 3x30 μm^2 HBT devices in dependence on the growth condition.

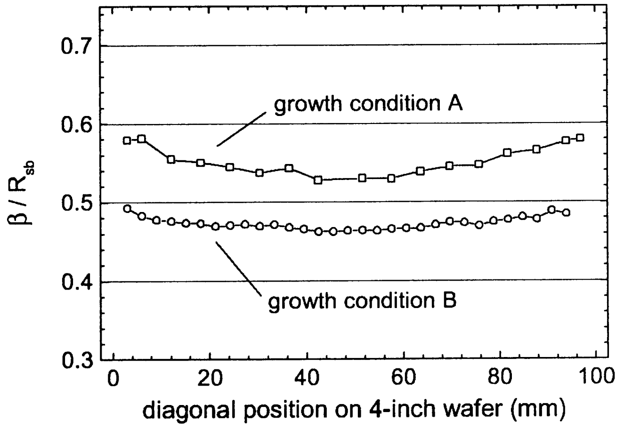

Fig. 3 Ratio of current gain to base sheet resistance for large area 60x60 μm^2 HBTs grown under different conditions.

The power added efficiency PAE reached 43% and 47% under class A operation, respectively.

Reliability tests were performed on single emitter finger 3x30 μm^2 HBTs at room temperature and at a high collector current density of $1x10^5$ A/cm^2. Typical results from burn-in measurements up to 60 hours are shown in fig. 4. Differences between wafers grown at different conditions A and B are mainly visible during the first 30 hours. The current gain of HBTs A increases by 5% very rapidly after the start of stressing. This increase is followed by a continuous decrease which becomes slower at a current gain value of 5% below the initial value. HBTs grown at condition B shows an immediate decrease of the current gain by 5% after starting the stress measurement. During the next 10 - 15 hours a slight increase of the current gain is observed. However, the initial current gain value is not reached. Subsequently, the current gain decreases slowly, similar as observed for HBTs A. The current gain changes are accompanied by a continuous increase of the emitter-base ideality factor (from 1.1 up to 1.4) for both HBTs A and B.

First long-term (up to 600 hours) stress measurements show similar results for the differently grown HBT wafers. In both cases the current gain decreases with a slope in the region of $5x10^{-2}$ per hour. After a stress period of 300 hours the decrease in current gain slows down to ratios of 10^{-3} per hour.

The different base growth conditions A and B seem to be responsible for the initial burn-in behaviours. Due to the complex nature of degradation mechanisms in HBT structures no clear correlations can be pointed out. Rearrangement of charged species (hydrogen, CH-complexes, defects) in the base layer could explain the rapid current gain changes. The steadly increase of emitter-base junction ideality indicates the deterioration of this interface. However, the differences are not caused by different hydrogen incorporation levels because the equal hydrogen concentration was measured by secondary ion mass spectrometry (SIMS) in base layers grown at conditions A and B. The material grown under condition B seems to give less „dramatic“ effect as only decrease in current gain was observed and the „stable“ value of -5% was reached sooner. However, the burn-in does not change the difference in the β/R_{sb}-ratios obtained at conditions A and B. This result indicates that the different base layer quality - as marked by the differently high current gains - is not strongly affected by stressing the HBT devices.

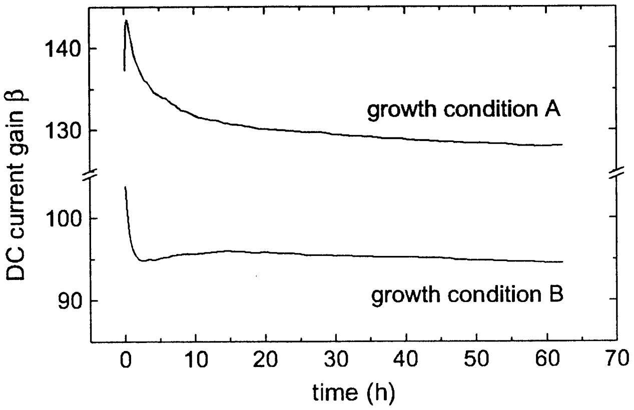

Fig. 4 Current gain changes during burn-in stress measurements for single finger 3x30 μm^2 HBTs grown under different conditions.

Further measurements, especially long-term stressing of sufficiently large specimen amounts, could trace out the dependences between growth conditions and HBT reliability. Further work including changed base doping conditions is currently performed [5].

CONCLUSIONS

MOVPE growth of high quality large area HBT wafers is still a challenge. Especially, optimizing the growth parameters for each layer in terms of single layer quality does not necessarlly lead to the best HBT device performance. Thus, a compromise between the single layer quality and overall HBT performance is required. Despite of this compromise state-of-the-art HBT subcells and L-band power cells were produced.

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