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Quasi-planar GaAs heterojunction bipolar transistor device entirely grown by chemical beam epitaxy

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Quasi-planar GaAs/GaInP heterojunction bipolar transistor (HBT) structures, fabricated with selective regrowth of an improved collector contact, are reported. Such devices present a planar surface topology which should allow large scale integration. The initial growth of the new HBT structure and the selective regrowth of the collector contact are performed by chemical beam epitaxy (CBE). In the case of the high C base doping level, the high temperature regrowth process induces some degradation of the HBT current gain which is analysed in terms of a decrease in minority carrier lifetime. Despite this effect, promising microwave performances are obtained with a cut-off frequency and maximum oscillation frequency of 30 and 25 GHz, respectively.

1. Introduction

Chemical beam epitaxy (CBE) is now recognized as a powerful growth technique for the realization of GaAs based heterojunction bipolar transistor (HBT) devices, mainly because of its capability to produce extremely high and stable p-type C-doping concentrations in GaAs, using trimethylgallium (TMG) precursor [1]. In addition, CBE is also the optimum growth technique for achieving selective area growth, which enables a three-dimensional control of epitaxial layers. These additional capabilities expand the flexibility of device and circuit design, and are of great interest for the simplification of the post-growth processing of epitaxial device structures and also the monolithic integration of III–V (opto)electronic components using selective growth processes.

In the conventional HBT technology, the wafer surface is etched back every time a new layer is accessed in the transistor structure. Consequently, device contacts are present at different depths from the surface down to typically 1 μm. The maximum step required for the collector contact is mainly determined by the thickness of the collector layer, which is optimized according to device specifications, such as base–collector capacitance and breakdown voltage. This results in a non-planar device structure which is a limitation for the formation of reliable metal interconnections and also for large scale integration.

In the present study, we have investigated a new HBT epitaxial process entirely based on CBE of GaAs and related materials, in order to obtain quasi-planar HBTs. The final surface step height is reduced to less than 0.3 μm by a selective regrowth of the collector contact on the subcollector layer, the base and emitter surfaces being covered by a dielectric mask. A direct advantage of this technological approach is the improvement of the collector contact, since a GaInAs contact layer can now be grown on top of the regrown subcollector. Such a contact provides a low Schottky barrier, which is found to be effective in obtaining very low resistivity ohmic contacts without alloying, in a way similar to that which has already been realized for the emitter contact [2]. A similar solution has already been reported for the improvement of the base contact by a selective CBE regrowth of a heavily C-doped extrinsic base layer [3]. Thus, in the future, the

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collector, base and emitter regions could be contacted at the surface of the device with the same contact material such as a refractory tungsten metal which allows patterning by reactive ion etching (RIE). This leads to a simplification and to a higher reliability of the contacting of the resulting integrated circuits.

The CBE selective growth conditions for this application have been studied recently [4]. The present paper is focused on the HBT current gain degradation observed after the thermal treatment required for the selective regrowth. This thermal degradation is analysed in terms of the minority carrier lifetime in the C-doped GaAs base layer, measured by photoluminescence decay, and has been investigated versus C-doping level, growth conditions and annealing temperature in order to reduce such degradation.

We also report the successful validation of this technological approach by the measurement of promising microwave performances of a quasi-planar C-base-doped HBT device produced with a selectively regrown collector contact.

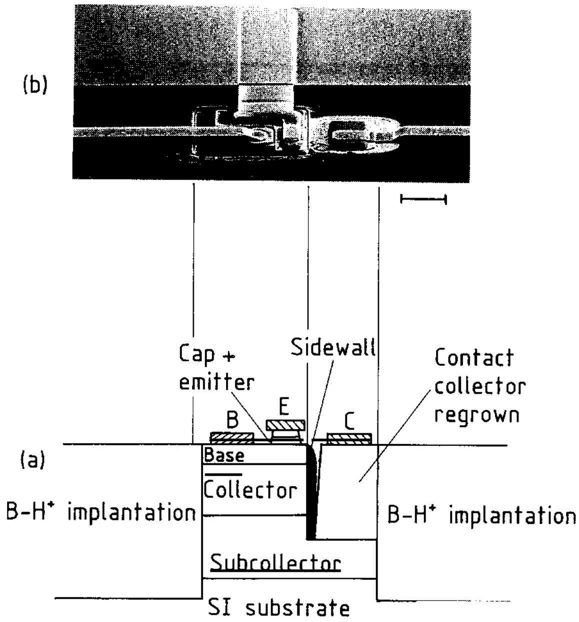

Fig. 1. Cross-sectional view (a) and SEM surface micrograph (b) of the final quasi-planar HBT after the collector contact regrowth process. The marker refers to 5 μm scale.

2. Growth procedure for the quasi-planar HBT process

The starting HBT epitaxial structure, described in table 1, is grown by CBE on a (100) semi-insulating GaAs substrate using conventional group V hydrides and group III organometallic sources. The n- and p-type dopants are provided from solid silicon and trimethylgallium sources, respectively. A low growth temperature of 500°C is used for the whole structure. The HBT has a specific emitter bilayer structure made of two high-bandgap semiconductors: a 30 nm thick $Ga_{0.52}In_{0.48}P$ layer is inserted between the C-doped base layer and the $Ga_{0.7}Al_{0.3}As$ emitter layer. Among many advantages [5] of this emitter bilayer structure, the etching selectivity, when using either chemical or plasma etching, between GaInP and GaAs offers the possibility to contact the base layer very easily. This overcomes the main difficulty of the-current HBT technology, and very good ohmic base contacts are obtained, even on very thin base layers.

Table 1
HBT initial structure

Cap E′	n^+-$Ga_{0.35}In_{0.65}As$	Si: 10^{19} cm^{-3}	50 nm
	n^+-$Ga_{1-x}In_xAs$	Si: 10^{19} cm^{-3}	50 nm
	n^+-GaAs	Si: 2×10^{18} cm^{-3}	50 nm
Emitter E	n-GaAlAs	Si: 4×10^{17} cm^{-3}	170 nm
	n-GaInP	Si: 4×10^{17} cm^{-3}	30 nm
Base B	p^{++}-GaAs	C: 6×10^{19} cm^{-3}	110 nm
Collector C	n^--GaAs	Si: 2×10^{16} cm^{-3}	490 nm
Subcollector C′	n^+-GaAs	Si: 2.5×10^{18} cm^{-3}	510 nm
GaAs SI substrate			

The structure of the selectively regrown collector contact is similar to that of the emitter contact and consists of 1 μm thick n^+-GaAs (5×10^{18} cm^{-3}) followed by 100 nm n^{++}-$Ga_{1-x}In_xAs$ (1×10^{19} cm^{-3}) with a graded In composition of up to 0.65. Fig. 1 shows a schematic cross section and a scanning electron microscope (SEM) view of the quasi-planar HBT. The regrowth regions are previously defined by opening windows in a 1000 Å thick Si_3N_4 mask deposited on the whole wafer by plasma enhanced chemical vapour deposition (PECVD). Then a vertical $SiCl_4$ reactive ion etching of the HBT structure through the mask windows is achieved from the emitter cap down to the subcollector layer. Si_3N_4 vertical spacers, deposited by PECVD and etched by reactive ion etching (RIE), ensure the lateral isolation between the regrown collector contact and the other HBT active layers. A specific surface preparation, consisting of a 100 Å deep chemical etching followed by UV assisted ozone treatment, and a few minutes of silicon predeposition prior to the regrowth, are applied in order to minimize the residual carbon surface contamination and to ensure the n^+-type continuity at the regrowth interface [4].

The CBE selective regrowth of GaAs and GaInAs is performed at substrate temperatures of 650 and 550°C, respectively. A high 2.5 μm/h GaAs growth rate is used in order to minimize the time of the thermal treatment corresponding to the regrowth. With such growth conditions, a perfect growth selectivity is obtained with absolutely no deposition on the dielectric mask, and the layer exhibits a high thickness uniformity. A slight growth rate enhancement (only a few percent of the selective regrowth thickness) is observed only in the vicinity of mask edges, due to the migration of species from the slow growing (111) sidewall planes. Furthermore, we have obtained recently, after optimization of the selective GaAs growth conditions, vertical sidewalls without lateral overgrowth [10]. These two features, which are specific to the CBE technique, are required for the easy removal of the mask and for the realization of a planar surface.

The final technological steps are the device isolation by ion implantation, the emitter and collector contacting by a 3000 Å thick tungsten film, and the C-doped base contacting by Mn–Au–Ti–Au ohmic contact through the GaInP layer, after the GaAlAs emitter mesa has been formed by selective etching.

All these different technological steps are realized on 2 inch wafers. For the two CBE growth steps, the wafer is mounted indium-free and heated radiatively through a boron nitride diffusing plate. The growth temperature is monitored by an optical pyrometer working at a wavelength of 0.94 μm.

3. Static quasi-planar HBT characterization

Transmission line measurements (TLMs) were used to extract the electrical parameters of the collector contact regrowth. A resistivity contact as low as 10^{-6} Ω cm^2 has been obtained for a 1 Ω contact resistance.

Static performances have been obtained on HBTs with a 2×15 μm^2 emitter–base junction area and a 6×15 μm^2 collector–base junction area. A common emitter current gain (β) of 2.5 for a base sheet resistance of 140 $\Omega/\square$ was measured, with a breakdown voltage of the collector–base junction BV_{CEO} above 15 V. This β value is low, as compared to the value of 23 measured on a similar HBT structure processed with a low temperature conventional double-mesa technology, although the base sheet resistance is constant within 10%.

This degradation of current gain after the thermal treatment required for the regrowth process cannot be attributed to a base dopant diffusion towards the emitter layer, as shown by secondary ion mass spectrometry (SIMS). More precisely, the same low value of 1.21 V for the emitter–base threshold voltage is measured for both the low temperature conventional HBT technology and the high temperature technology with the regrowth process. This threshold voltage, defined as the emitter–base voltage required to generate a fixed value of the collector current, has been found to be extremely sensitive to base dopant diffusion, and the low measured value agrees well with a simulation without dopant diffusion [6]. This behaviour is in accordance with the high thermal stability of C dopant in GaAs.

In order to determine the origins of the device performance degradation, we have performed some measurements by time-resolved photoluminescence, of minority carrier lifetime in C-doped GaAs layers sandwiched by undoped GaAlAs lay-

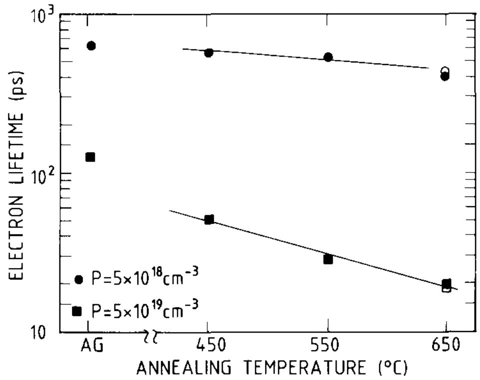

Fig. 2. Electron lifetime in C-doped GaAs layers for two different C doping levels, as a function of annealing temperature and also compared to the value in the as-grown (AG) material. Full circles refer to a 60 min annealing time and open circles refer to 15 min annealing time under cracked AsH_3. In this latter case, same values are also presented for annealing under As_4 pressure.

ers. The purpose of the double heterostructure is to confine induced carriers in the p-type GaAs layer and to eliminate the influence of surface recombination. Fig. 2 shows for two C doping levels (5×10^{18} and 5×10^{19} cm^{-3}), the evolution of electron lifetime as compared to the as-grown sample and as a function of annealing temperature (450, 550 and 650°C for 1 h and under AsH_3 pressure). The observed behaviour is not drastically changed with a shorter annealing duration (15 min) or under a hydrogen free pressure (As_4). The electron lifetime decrease is more pronounced for high C concentrations and also for high annealing temperatures. In the case of a thermal treatment at 650°C, corresponding to the applied regrowth process used, the same decrease of about one order of magnitude for a C-doping level in the mid-10^{19} cm^{-3} range is found both for the minority carrier lifetime and for the HBT current gain. This correlation follows well the dependence of the current gain β with the electron lifetime in the base layer τ according to the relation:

$$\beta \approx \tau / \tau_{EC},$$

where τ_{EC} is the transit time of electrons from the emitter to the collector. This demonstrates that the thermal degradation of the HBT current gain is directly related to the reduction of minority carrier lifetime after anneal. Similar results on samples grown by metalorganic chemical vapour deposition have been found in our own study and in ref. [7].

To investigate the mechanism causing the minority carrier lifetime change with annealing, the corresponding variation in concentration of both carbon and hydrogen atoms were measured by SIMS, with detection limits of 1×10^{17} and 4×10^{18} cm^{-3}, respectively. In the case of C-doping levels higher than 5×10^{19} cm^{-3}, we can detect a hydrogen content which amounts to more than 10% of the C content in the as-grown layers, and which decreases drastically to lower than the SIMS detection limit, after annealing at 650°C. There has been evidence that hydrogen is incorporated into the C-doped layer along with carbon, via the incomplete decomposition of trimethylgallium species [8]. We think therefore that the reduction of electron lifetime after anneal is related to the exodiffusion of hydrogen atoms. We speculate that the unstable behaviour of the highly C doped layers must be due to deep levels already present in the as-grown material. Such defects might be hydrogen passivated in the as-grown layer and are then revealed when the hydrogen is removed during high temperature thermal treatment [9].

From the present data, it appears that a reduced thermal degradation of the minority carrier properties, compatible with a sufficient HBT current gain, can be obtained in the case of C doping concentrations of up to 2×10^{19} cm^{-3} and for selective regrowth temperature lower than 650°C. This critical temperature can be decreased down to 550°C by using a reduced 0.8 μm/h selective growth rate when growing with the use of a triethylgallium (TEG) precursor [10], and down to 450°C in the case of a TMG source [11]. In this way, the thermal degradation of HBT current gain has been reduced to a factor of 2 [12]. Moreover, we have recently succeeded in obtaining quite stable minority carrier properties of heavily C-doped GaAs layers up to 2×10^{20} cm^{-3} even after high temperature annealing, by atomic layer epitaxy using the alternative supply of TMG and arsine [13].

4. Microwave quasi-planar HBT characterization

The microwave measurements have been carried out on a Wiltron 360 network analyser. The S parameters of the HBTs are measured up to 40 GHz. The microwave current and power gains are displayed in fig. 3, for a current density of 4.5×10^4 A/cm^2 and HBT bias conditions of $V_{EB} = 1.5$ V and $V_{CE} = 3$ V. A cut-off frequency, F_t, of 30 GHz and a maximum oscillation frequency, F_{max}, above 25 GHz have been measured. The latter frequency is extrapolated from the main part of the power gain curve with a -6 dB/octave. These first microwave performances on the planar HBT devices obtained using the selective regrowth collector contact are already comparable with values obtained with a conventional multi-mesa technology.

5. Conclusion

In summary, we have presented a new quasi-planar GaAs/GaInP HBT technology. The main technological step is the selective CBE regrowth of an improved collector contact from the bottom subcollector layer up to the emitter layer, which allows a quasi-planar device to be realized. In the case of a high temperature regrowth process, and of C-base doping levels above 2×10^{19} cm^{-3}, a degradation of the HBT current gain has been found and has been correlated directly with a decrease of minority carrier lifetime in the base layer. It has been proposed that this behaviour for high C concentrations must be due to deep centres already present in the as-grown material. We suggest that these defects are passivated by the hydrogen present in the as-grown layer and are then revealed when hydrogen is removed during the high temperature thermal treatment. Despite this effect, promising microwave performances of 30 and 25 GHz for F_t and F_{max}, respectively, have already been obtained.

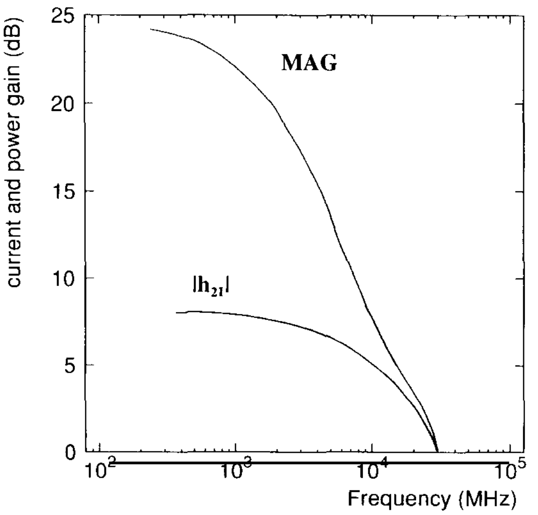

Fig. 3. Current gain and power gain of the 2×15 μm^2 quasi-planar HBTs versus frequency.

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