The Reliability of III-V semiconductor Heterojunction Bipolar Transistors

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The Heterojunction Bipolar Transistor (HBT) features some characteristics that make it a very promising device in the telecom field. For these applications, the reliability is a key issue.

The aim of the present paper is to summarise the most relevant reliability concerns, from whose the HBT suffers, as the stability of the ohmic contact, the presence of defects, and the stability of the base dopant. Since in the last years the Si/SiGe HBT has emerged as a strong competitor against the III-V HBT, a paragraph has been devoted to summarise the reliability concerns of the Si/SiGe HBT.

INTRODUCTION

The HBT features specific characteristics that make it a very interesting device. Being a bipolar transistor, the HBT shows good capability in terms of power handling and breakdown voltage and it is therefore suited for the fabrication of power amplifiers. The HBT exhibits also low 1/f noise levels and therefore it can be useful employed for the fabrication of oscillators and mixers. In addition, the HBT exhibits a high uniformity of the threshold voltage and a high transconductance. These properties make the HBT a very well suited transistor for the fabrication of high speed logic circuits and/or Analog-Digital Converters.

In spite of these interesting characteristics, the HBT suffers from reliability concerns, that are today not still full solved. Their solution is a key issue to move the HBT from the R/D laboratories to the real telecom applications, which demand high reliability devices.

Aim of the present work is to summarise the most important HBT reliability concerns.

The paper is organized as in the follow. The first paragraph focuses on the metallurgical system employed for the fabrication of the ohmic contact, in particular, the stability of the base ohmic contact. The second paragraph addresses the topic of the point and extended defects in the HBTs. Their correlation with and their influence on the HBT reliability will be pointed out. The third paragraph is devoted to the base dopant stability, which is still today the most relevant HBT reliability concern. The two most widely employed doping impurities are the Beryllium and the Carbon. Each of these impurities suffer from specific instabilities. The mechanism of these instabilities and their effects on the device performance will be addressed.

Since in these last year the Si/SiGe HBT has emerged as a very strong concurrent to the III-V compound HBT, a paragraph will be devoted to the reliability of the Si/SiGe HBT.

Finally, some conclusions will be drawn at the end of the paper.

OHMIC CONTACTS

The increase of the resistance of the ohmic contacts during the device operation is considered as the main issue for the ohmic contact stability. In the HBT technology both n- and p-type ohmic contacts are required.

n-type contacts

For the n-type contacts, technologies similar to those employed for the High Electron Mobility Transistors (HEMTs) are used. Nevertheless, with respect to the HEMT technology, a larger sensitivity is expected due to thinner layers involved in the HBTs. Diffusion barriers and not alloyed contacts were therefore proposed. For example, AuGe/Ni/Ti/Au alloyed contacts to n-type GaAs degrade under thermal stress due to the interaction between the Au of the metal system and the Ga of the semiconductor. It has been demonstrated that the insertion of a Pt barrier layer (therefore the contact becomes AuGe/Ni/Ti/Pt/Au) inhibits the Au diffusion (1). By contacting semiconductors containing Indium (e.g. InGaAs/Ni/W), the In diffusion to the contact surface can deteriorate the ohmic contact. Even in this case, it has been demonstrated that the insertion of a barrier layer (e.g. W_2N layer between the Ni and W layers) prevents the In diffusion and it improves the thermal stability of the ohmic contact. Recently, it has been reported that the degradation of ohmic contacts on a n-InGaP layer (e.g. emitter layer) can be induced by exposure to high energy (1MeV) electron irradiation (dose $1.2\text{-}5.10^{-15}$ cm^{-2}). It has been found that the same exposure did not affected the collector contact made on the InP sub-collector layer.

p-type contacts

As for the contacts on p-GaAs, systems using refractory materials were investigated, such as Pt/W/Ag, Pt/Zn/Au and Pt/Ti/Pt/Au. It was demonstrated that these contacts are reliable under thermal stress and provide also low resistivities (2). Ti and Mo layers were inserted into a conventional Pt/Ti/Pt/Au system in order to improve the thermal stability of the InGaAs base contact. After 30 minutes of thermal stress between 350°C and 430°C, this new structure (Pt/Ti/Mo/Ti/Pt/Au) showed a slighter contact resistivity increase than the traditional Pt/Ti/Pt/Au contact. Different metal systems (Pt/Ti, Au/Ti, Au/Pt/Ti; Au/Pt/Ti/W) on InGaAs base layers have been investigated and it was found that the use of refractory metals as a diffusion barrier improves the contact stability under thermal stress (3). It was also demonstrated that the stability of the commonly employed Ti/Pt/Au metalization can be improved by replacing the Pt with a ZrB_2 layer, being therefore Ti/ZrB_2 the new metalization (4). Recently the barrier properties of layers of TiN, ZrB_2 and W_2B in Au-based metallization have been demonstrated through Rutherford Backscattering Spectroscopy (RBS) (5).

The stability of the p-contacts is a very critical issue in the HBT reliability, because typically the p-layer to be contacted is the base. Since the base layer of a HBT is very thin, the concern of the p-contact stability is not only limitated to the increase of the contact resistance but also to the base metal penetration. Indeed, this penetration can lead to a serious degradation or even to the short circuit of the Base-Collector junction.

Also the extrinsic base surface of the HBT is critical under a metallurgical point of view. Maneux et al. (6) detected through Energy Dispersive Spectroscopy (EDX) measurements a metal atom migration induced by high electric-fields in the GaAs extrinsic base region, as a consequence of the bias aging. Similar results were reported also by Schûssler et al (7) as a consequence of applying pulsed Electro Static Discharge (ESD).

POINT AND EXTENDED DEFECTS

The generation of point defects in the base-emitter space charge region during the bias aging (8,9)or as effect of the irradiation with electrons or neutrons was oft reported as responsible for an anomalous base current exhibiting an ideality factor larger than two (10). The generated defects are midgap traps, that make possible the injection of electrons through a trap-assisted band-to-band tunneling from the emitter into the base, where they recombine with holes, giving rise to the anomalous recombination contribution to the base current (8-10). Another possible mechanism for the anomalous base current contribution is identified as a non-uniform distribution of Schockley-Read-Hall recombination centres located in the depletion layer (8-10).

Defects may be generated also in presence of fabrication process-induced damage. The dry etching technique offers the advantage of a better uniformity and reproducibility on large areas with respect to the less damaging wet etching technique and therefore it has to be preferred for the fabrication of integrated circuits. On the other hand, it is known that the ion etching induces surface damage, because of the bombardment of the high energy ions of the plasma (11). It was demonstrated that the damage caused by the dry etching, employed for the fabrication of AlGaAs/GaAs HBTs featuring half-micron emitter width, largely affects the device reliability (12). It has been shown that the DC current gain of devices, where the dry etching damage was not removed, degrades quickly during an electrical stress. This was attributed to recombination centres created during the life test as a consequence of the combination of the ions damage and of the minority carriers injected by the base-emitter junction.

The extended defects largely affect the reliability of the HBTs. Electroluminescence (EL) investigations showed that the degradation occuring during a life test is associated to the Dark Line Defect (DLD) (13), as already observed in Light Emitting Diodes (LEDs) and Laser Diodes (LDs) (14). In these optical devices the DLD are associated to extended defects, typically dislocation networks resulting as a consequence of the stress. Through Transmission Electron Microscopy (TEM), Ren et al. (15) found extended defects at the collector/subcollector interface after a bias stress. It is speculated that these extended defects may result from the condensation of point defects migrating during the stress even if their nature should still be better clarified.

Extended defects in proximity of the base-emitter junction can be detected also through Cathodoluminescence (CL) measurements (5). Recently, it has been reported that dislocations can be generated during an electrical stress; the higher the stress current density, the higher the increase of the dislocation density during the stress time (16). Through comparisons between the activation energies obtained from experimental data and from numerical simulations it has been suggested that a model of the dislocation dynamic in a HBT under current stress should take into account Recombination Enhanced Defect Reactions (REDR) (16), a general set of solid-state reaction introduced in the 1978 by Kimerling (17).

THE BASE DOPANT STABILITY

Even if the previous reliability concerns are important, the primary HBT reliability issue is the base dopant stability. Beryllium and Carbon are today the most widely employed base doping impurities. The challenge between Beryllium and Carbon is very actual in the design strategies of built-in reliable HBTs. TRW is currently fabricating HBTs featuring a Beryllium doped base (18) while Kopin has demonstrated Carbon doped HBTs exhibiting impressive reliability performance (19). At the present, it is not still clear which acceptor impurity is better or if the use of one instead of the other should be chosen on the basis of the specific application.

The Beryllium as base dopant

The Beryllium diffusion from the base into the emitter during the HBT operation is the most serious concern in using this impurity as the base dopant. The typical DC effect of Beryllium outdiffusion is the increase of the threshold voltage, which causes the degradation of the collector current (20, 21).

Even if the threshold voltage is a very sensitive indicator of Beryllium outdiffusion, researchers involved in HBT technology development have introduced alternative electrical parameters enabling to detect this degradation mechanism. The most significant of these parameters is the inverted collector current ratio R, defined as the ratio of the inverted collector current measured at two different voltages applied to the base-emitter junction (22).

Numerical simulations have demonstrated that the increase of both the threshold voltage and of the ratio R can be explained in terms of electron thermoionic emission over a parasitic potential barrier created, at the base-emitter junction, as a consequence of the Berylllium diffusion towards the emitter (22,23). Other DC effects are reported as due to the Beryllium diffusion towards the emitter, such as the increase of the offset voltage and the increase of the ideality factor of the collector current (21).

The Beryllium outdiffusion also affects the RF performance (21) and experimental data demonstrate that the DC and RF degradations are fully correlated (24). The base dopant outdiffusion causes a decrease of the DC current gain, which is mirrored by the decrease of the RF current gain |h21| when |h21| is measured, before and after the stress, at the same base current. On the other hand, the degradation is very reduced when |h21| is measured after the stress at the same collector current as before (24). This result has important practical implications, because it demonstrates that a bias arrangement whereby the collector current is kept constant will automatically compensate the threshold voltage shift, minimising the RF effects of the stress.

The degradation of the collector current increases with increasing the Beryllium concentration in the base layer (25). It was suggested that the Beryllium concentration in the base layer should be limited to 10^{19}cm^{-3}, in order to have a reliable device (15). The concentration dependent diffusion process can be described through a substitutional-interstitial diffusion mechanism, that can involve Gallium vacancies (26), or Gallium interstitials (kick-out) (27, 28). Today the substitutional-interstitial diffusion of the Beryllium is accepted to follow the kick-out mechanism.

The degradation related to the Beryllium diffusion was not observed when the device was purely thermal stressed under temperatures ranging between 200°C and 280°C (29) without bias or at least only a small increase of the threshold voltage was revealed after a very high temperature storage (500-525°C) (25). The degradation of the device under test occurs (29) or is accelerated (25) when the base-emitter junction is forward biased.

The similitude of the electrical-current-induced acceleration of degradation observed between HBTs and tunneling diodes suggests that the same mechanism occurs in both the devices (30). Uematsu and Wada proposed a recombination Enhanced Impurity Diffusion (REID) mechanism (30), which is a particular case of REDR (17). In the REID mechanism the recombination injected minority carriers causes the annihilation of non-radiative recombination centres, which is then followed by the emission of a defect, which is believed to be a Gallium interstitial, on the basis of the substitutional-interstitial diffusion mechanism. It has been demonstrated that the Beryllium diffusion induced by current stressing the base-emitter junction of a HBT is associated with the increase of the cathodoluminescence (CL) integrated intensity (31). The increase of the CL signal well agrees with the annihilation of non-radiative recombination centres contemplated by the REID model.

Since the Beryllium diffusion is interstitial-substitutional REID diffusion, a particular care must be taken during the wafer growth, in order to avoid interstitial Beryllium atoms and defects, that, on the basis of the REID mechanism, can enhance the formation of interstitial Beryllium and therefore boost the HBT degradation during the device operation. With the idea of that, during the wafer growth, Be adatoms are able to migrate to the step edge and to be incorporated into substitutional rather than interstitial sites, several methods have been proposed, such as the use of a very high V/III ratio, the growth on a few degrees misoriented (100) surface, the growth on the (311) plane, and the growth under weakly As-stabilised condition at a low value of the V/III ratio (32).

The diffusion of interstitial Beryllium can be inhibited thanks to its dependence on the mechanical strain (30), as demonstrated by the insertion of a nine-period superlattice (33) or of a pseudomorphic tensilely strained layer (34).

The epitaxial structure of the HBT can be designed, in order to be less sensitive to the Beryllium outdiffusion. HBTs featuring a graded base-emitter junction or an undoped setback layer between base and emitter demonstrate a lower sensitivity to the Be diffusion even if the base dopant diffusion through the undoped setback can induce small negative shifts of the threshold voltage (35).

The Carbon as base dopant

A solution, in order to avoid the base dopant outdiffusion, is to change the acceptor impurities. Under this point of view, the Carbon is a very interesting choice. It exhibits a very low diffusion coefficient thanks to the fact that in the GaAs crystal the Carbon atoms occupy the Arsenic instead of the Gallium sublattice, as it is the case of the Beryllium (36).

Despite of this important advantage, the Carbon suffers from instability issues, specially related to Hydrogen contamination. The largest amount of Carbon doped wafers for HBT fabrication are grown by MOCVD, where the Hydrogen is employed as a carrier gas. Hydrogen can be adsorbed also during plasma depositions (e.g. SiN) (37), introduced by a proton implant isolation (38) or during a plasma etch (39). In presence of Hydrogen, the C atoms tend to be passivated, giving rise to electrically inactive C-H complexes (40). In the GaAs crystal the Hydrogen can act also as donor, compensating therefore the acceptor ionised Carbon. The Hydrogen atoms are incorporated as Carbon passivators for concentrations up to $3\text{-}4\cdot 10^{18}\text{cm}^{-3}$ and as donors for higher concentrations (41). During the electrical stress, the C-H complexes are broken by the injected minority carriers and the activated base dopant concentration increases, as a consequence. This turns out in a decrease of the DC current gain (42).

When the Hydrogen contamination is low, as in the case of GSMBE grown samples, the electrical stress leaves the DC current gain unchanged (43). Also the HBTs fabricated by using MOCVD grown material in-situ annealed at 600°C, exhibit a stable DC current gain during the electrical stress (42). Excellent long term reliability was demonstrated also by MOCVD grown HBTs, in which the base layer was Carbon doped without making use of any dopant precursor (19).

The contamination of Hydrogen is believed even to be responsible for the early increase of the DC current gain (the burn-in effect) frequently observed during the electrical stress of HBTs with a Carbon doped base layer (44, 45, 46). The annihilation of Hydrogen related recombination centres (e.g. H^0, H^+) (44) or the passivation of surface defects at the passivation/semiconductor interface in the extrinsic base region during the stress (45, 46) have been proposed as possible mechanisms responsible for the burn-in effect.

The Carbon impurities do not suffer only from instabilities related to Hydrogen contamination. Because of its low covalent bonding radius, the high Carbon concentrations typically employed in the base layer of HBTs tend to shrink the GaAs lattice constant. For ultra-high Carbon doped base the Carbon induced lattice shrinkage may be so high that the lattice mismatch between base and emitter causes threading dislocations to grow into the emitter (47). The addition of Indium reduces the lattice shrinkage (48). It was demonstrated that HBTs featuring a Carbon/Indium doped base layer exhibit an improved stability during electrical life tests (48).

Recently, relevant improvements of the stability of GaInP/GaAs HBTs have been demonstrated, as it will be reported during the conference (49).

The Si/SiGe HBTs

In these last years the SiGe based HBT is strongly emerged as a very competitive alternative to the III-V compound semiconductor HBT. Nevertheless, it should be pointed out that a given typical high frequency figure-of-merit, as the cutoff frequency, can be reached in the SiGe technology only by using a base layer thickness thinner than in the III-V technology (50). For example, in order to obtain a cutoff frequency of about 60GHz, a SiGe HBT needs a base thickness of around 30nm while a III-V HBT needs a thickness of 60nm. This requires a very high stable base ohmic contact, in order to avoid a serious damage or the short circuit of the base-collector junction, as already shown in the previous paragraph on the ohmic contacts..

For applications in a very high frequency range (higher than 100 GHz) the III-V HBT technology is better suited than the SiGe HBT one. On the other hand, the great advantage offered by the SiGe HBT technology over the III-V one is its compatibility with the silicon BiCMOS technology. This allows to introduce the concept of HBT into the standard silicon technology and this justifies the great expansion shown by this technology in these last years. Moreover, it has also to be pointed out that many applications in the field of wireless communications do not require high performance levels (e.g. f_{max} up up to 100GHz).

In any case, the reliability still remains a key issue also for the SiGe HBT technology.

The typical life test for Si/SiGe HBTs is the electrical stress of the base-emitter junction under reverse bias with the collector left open (51). In this case the junction is stressed by hot holes generated by the high electric field present at the reverse biased base-emitter junction.

A current accelerated method has also been proposed (52,53), where the base-emitter junction is still reverse biased but the base-collector junction is forward biased, in order to supply additional hot carriers (electrons). In this case, the base-emitter junction is stressed by hot electrons. The effects of the two stresses are similar. It has been observed an increase of a base current component in the low base voltage range in the Gummel plots, being around two its ideality factor. This stress induced base current component has found to be associated with the increase of a lorentzian component in the equivalent input-referred base current low frequency noise spectra (53). In particular, even if the effects are similar, the low frequency noise measurements have demonstrated that the hot holes induced a larger degradation than the hot electrons. Therefore, the two stresses cannot be considered really as equivalent.

Stresses carried out on devices featuring different emitter perimeter-to-area ratios have suggested that the degradation may occur at the spacer-oxide along the emitter perimeter (51,54). The degradation mechanism has been reported to be the bond break at the Si/SiO2 interface. The rate of the bond breaking strong depends on the hot carriers kinetic energy and therefore stresses employing holes or electrons as hot carriers cannot be considered as equivalent, in agreement with the previous experimental observations.

It has been found that the Germanium content and profile do not impact on the reliability of SiGe HBTs and that, for given stress conditions, the induced degradations are the same in SiGe HBTs and in similar Si BJTs (52,53). The same values of Time-To-Failure (TTF) as function of the inverse base-emitter junction bias have been found for SiGe HBTs and Si BJTs both for stress performed with the collector left open or with the base-collector junction forward biased (52).

Also the robustness of the SiGe HBTs to the irradiation has been tested in the perspective of possible space applications. As in the case of the III-V HBTs, an anomalous component of the base current characterised by an ideality factor larger than three has been observed as a consequence of fast neutron irradiation (55). The degradation was ascribed to deep levels induced in the SiGe layer.

In contrast to the electrical stresses, a dependence of the irradiation induced degradation on the Germanium content was reported. It was observed that the degradation decreased with increasing the Germanium content (55). The behaviour was ascribed to the property of the Germanium atoms of acting as recombination centres of interstitials and vacancies (56). This defect annihilation property decreases the rate of accumulation of irradiation induced defects, decreasing therefore the HBT degradation rate, as a consequence.

CONCLUSIONS

The most relevant HBT reliability issues have been considered, as the stability of the ohmic contacts, the presence of defects and the stability of the base dopant

Concerning the ohmic contacts, they degrade under thermal stress conditions. It has been pointed out that their stability is improved by making use of barrier layers, in order to prevent diffusion processes between metal and semiconductor, reducing their degradation during the thermal stress. Ohmic contacts degrade also as a consequence of exposure to high energy electrons.

The presence of defects negatively affects the HBT reliability. They can be detected by using of microanalysis techniques, as TEM, CL, and EL. In particular, it should be underlined that the extended defects (e.g. dislocations) largely reduce the transistor reliability.

As for the base dopant, the Beryllium and the Carbon have been addressed. The Beryllium suffers from disposition to diffuse from the base into the emitter while Carbon exhibits a low diffusion coefficient but it responsible of lattice shrinkage and transistor instabilities related to the formation of C-H complexes with detrimental effects on the reliability.

In summary, in spite of the fact that the HBT exhibits very interesting performance, it suffers still from different reliability concerns. The comprehension of the physical mechanisms affecting the reliability of this device is still an open problem and many efforts are therefore required, in order to make the HBT a device available for real applications requiring high reliability (e.g. telecom, military and aerospace applications).

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