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Photo-luminescence and transmission electron microscope studies of low- and high-reliability AlGaAs/GaAs HBTs

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Abstract

AlGaAs/GaAs single HBTs from two different epi-layers with similar layer design, but with some variations in layer properties due to the particular features of individual epitaxial growth techniques, were simultaneously fabricated using a self-aligned process. These HBTs were tested for their reliability characteristics as well as their material quality using photo-luminescence and transmission electron microscopy. HBTs from one epi-layer showed high reliability characteristics and presented smaller carrier recombination lifetime ($\tau_B \approx 150$ ps) in the base compared to devices from the other epi-layer ($\tau_B \approx 60$ ps), which showed low reliability characteristics. Using XTEM images, it was found that devices with higher degree of reliability show abrupt base-emitter junction vs low-reliability devices, which appeared to have compositionally graded base-emitter hetero-interface. © 2000 Published by Elsevier Science Ltd. All rights reserved.

1. Introduction

The long-term reliability of heterojunction bipolar transistors (HBTs) has been the subject of research by many groups, and over the last decade, it has shown a steady improvement [1–3]. The failure mechanisms responsible for the reliability characteristics of HBTs correspond to the crystalline quality, dopant diffusion, excessive leakage current at higher temperatures and contact as well as passivation layer failure [4]. The measure for the reliability of any device is the median time to failure (MTTF), which is usually found from accelerated stress tests. Such stress tests on AlGaAs/GaAs HBTs have shown a record high MTTF value of 10^9 h at a junction temperature of 120°C [1]. InP-based HBTs have achieved MTTF values in the order of 10^7 h at a junction temperature of 125°C [5], while GaInP/GaAs HBTs demonstrated MTTF values of 10^6 h at a junction temperature of 200°C [6].

One of the techniques used by many researchers to improve the reliability of HBTs is to grow the HBT layer structure at lower temperature to suppress positively charged interstitial dopants and avoid redistribution of charge under stress conditions [7]. Another method suggested in the literature is using improved passivation techniques in addition to use of ledge to suppress non-ideal base currents in HBTs [3]. The use of non-alloyed contacts and also InGaAs emitter cap to improve ohmic contact stability can also help in improving the reliability characteristics of these devices [8]. To suppress the stress formed in very heavily-doped base of high-performance HBTs, In co-doping of the base has been suggested in AlGaAs/GaAs HBTs

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[9]. For GaInP/GaAs HBTs, the employment of C-doped GaInP emitter in conjunction with C-doped GaAs base suppresses the performance sensitivity of the device to dopant redistribution and thus improves the reliability characteristics in these devices [10].

In designing high-reliability HBTs, one aims at obtaining minimum variation of physical parameters such as doping concentration, density of traps and dislocations and the quality of the hetero-interface as the devices age. Some of these physical parameters can be controlled, such that their variation does not impact the device performance significantly. For example, in GaInP/GaAs HBTs, although C-doping is used only in the base region, diffusion of this dopant to the emitter does not result in shifting the junction interface, since carbon has an amphoteric nature. As a result, the characteristics can remain stable, at least as for dependence on base dopant diffusion is concerned, and reliability can be improved.

Unlike dopant diffusion, propagation of traps and dislocations with temperature and electric field is less understood. The release of stress in a crystal can generate dislocations and the propagation of traps and dislocations is expected to lead to degradation of device characteristics. Lattice matching or use of very thin films of lattice mismatched and often stressed material with thickness below a critical value, are employed to ensure good material quality.

The heavily doped InGaAs often used as the emitter contact layer to reduce the emitter contact resistance and improve the device performance in GaAs HBTs can be a source of problems in terms of reliability. This layer is not lattice matched to GaAs substrate and although its thickness is kept to a minimum, it contains defects and dislocations. However, since it is the last layer in the growth of the HBT structure, the defects present in this layer are unlikely to propagate to the device active region and cause degradation. Although they trap a number of carriers in the contact region of the device, the HBT performance is not affected significantly since the carriers in this contact material are of majority type and a variation in their number or mobility does not cause significant deviation from nominal characteristics.

High spatial resolution transmission electron microscopy (TEM) allows study of HBT interface quality, regularity of structure, defects, layer thickness, and growth parameters [11]. TEM and cross-sectional transmission electron microscopy (XTEM) have been used to study the reliability of GaAs-based HBTs [6,12]. In most cases, the presence of defects or irregularity in the structure specifically in the base and close to the base-emitter region observed from XTEM could be used as a criterion for determining the device quality and its long-term reliability features [6,12].

Photo-luminescence (PL) measurements have also been used for material quality analysis in hetero-structures. Estimation of GaInP bandgap energy from PL peak and its variation with temperature at low temperatures can give information about the quality of GaInP material and whether it is ordered or disordered [13]. Excitation-dependent PL has been used to evaluate carrier life-time in the base and collector regions of HBTs [14–16].

TEM and PL characterizations are not the only techniques for HBT material quality evaluation. Other techniques such as electroluminescence and electrical measurement of non-ideal base current are among these techniques and have been used for studying the degradation mechanisms in HBTs [17], however such studies are beyond the scope of this paper and were not considered here.

Section 2 presents the reliability characterizations of HBTs studied here and discusses the similarity and differences between low and high-reliability devices. In section 3, the TEM analysis of low and high-reliability HBTs is presented, while section 4 presents the photoluminescence study of these devices. Results of the above analysis, as well as comparisons to the literature, are discussed in section 5, while the conclusion is presented in section 6.

2. Reliability characterization

The HBTs used in this investigation were fabricated on wafers grown by metal organic chemical vapor deposition (MOCVD) technique. Two different commercial vendors supplied the wafers used for HBT fabrication. Although the same layer design was attempted for all the wafers, small variations in layer properties or interfaces between layers are unavoidable due to the particular growth techniques used by the individual vendors. The 1000 Å base layer of the HBTs was doped with carbon at 4×10^{19} cm^{-3} concentration and a base sheet resistivity of 220–240 Ω/sq was measured for the HBTs. The collector layer was doped at 2×10^{16} cm^{-3} with a thickness of 10000 Å. A self-aligned emitter-base fabrication process was used to consistently fabricate base contact 0.4 μm away from emitter mesa edge. Silicon nitride was used as extrinsic base passivation. Non-alloyed Ti/Pt/Au contacts were used for emitter and base layers, whereas alloyed AuGeNi contacts were used for the collector. The eight finger 2.5×20 μm^2 HBTs from the two wafers revealed identical DC current gain (β) of 30 and very similar Gummel, β vs I_C and I_C–V_{CE} characteristics. The microwave characterizations of HBTs revealed f_T and f_{max} values of 60 and 100 GHz, respectively.

To identify the reliability characteristics of the HBTs, they were subjected to stress at 125°C under 25 kA/cm^2 collector current density. The stress conditions led to rapid degradation (within a few hours) of HBTs fabricated on the wafers supplied from one of the vendors, while HBTs fabricated on the wafers supplied from the other vendors did not show any degradation even after several thousands of hours. Devices that showed rapid degradation were termed "low-reliability" devices whereas devices that showed essentially no degradation at this stress condition were termed "high-reliability" devices. Fig. 1 shows the current gain variation as a function of time at 125°C junction temperature on the same device type fabricated with low and high-reliability wafers. Each device was biased at 3 V, and 25 kA/cm^2 emitter current density. The figure indicates that the degree of device reliability depends on the choice of material used for fabrication.

Different characterization techniques were used to analyze low and high-reliability wafers by evaluating the material properties. Low-frequency noise characterization of the fabricated HBTs revealed that high-reliability devices present smaller base and collector low-frequency noise than low-reliability devices [18]. In addition to low-frequency noise tests, material characterization studies were used and reported here to analyze the differences observed in reliability properties. TEM is a known technique for studying the regularity of crystalline structure and existence of defects in semiconductor materials [11,12]. A defect or crystalline irregularity in the active region of a device can cause performance degradation. It can also influence the long-term reliability of the device since these crystalline imperfections tend to propagate, especially under high electric field and elevated temperature stress conditions. Study of these defects and irregularity is helpful in understanding the limitations on the lifetime of an electronic device.

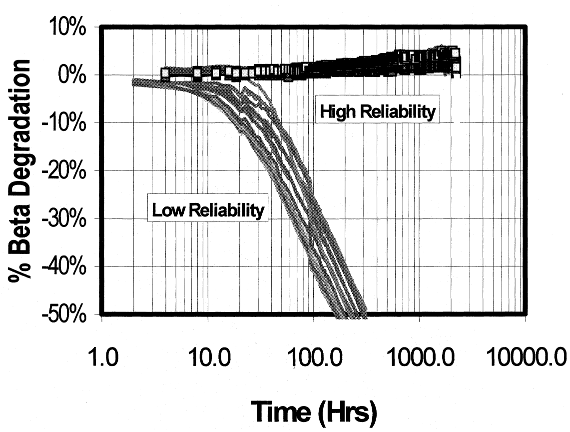

Fig. 1. Current gain variation of low and high-reliability HBTs vs time under 125°C temperature and 25 kA/cm^2 collector current density stress condition. The low-reliability HBTs degrade within 100 h while the high-reliability devices do not show any degradation under this stress test.

PL is another method that has been used to study the lifetime of carriers inside an electronic material [14]. If the carrier lifetime is short, the material may contain some defects that can be detected using this method. PL is a more sensitive tool than TEM in determining defect density since some of the defects present in the crystal may not be seen by an electron microscope. However PL does not provide quantitative information regarding the semiconductor itself and any imperfections existing in it, since it provides information not on the imperfections themselves, but the resulting semiconductor properties such as carrier lifetime. A combination of structures (TEM) and optoelectronic characterization techniques (carrier lifetime by PL) can therefore provide a more complete picture of the semiconductor and material dependent reliability properties. The results obtained from TEM and PL characterization of high and low-reliability HBTs are presented in the following sections.

3. TEM analysis of low- and high-reliability HBTs

TEM and XTEM have been previously employed for reliability analysis as discussed earlier [6,12]. Unlike previously reported results, the study performed here shows that despite the significant difference in reliability characteristics of the evaluated AlGaAs/GaAs HBTs, no significant variation was observed in their material quality. Fig. 2 shows the XTEM picture of the low-reliability HBT wafer, while Fig. 3 shows the XTEM of the high-reliability wafer. The wafers were first cleaved into pieces of suitable dimensions for TEM analysis and two pieces were glued face-to-face, polished with diamond film and bonded to support rings. The samples were then mechanically thinned using SiC paper and a Gatan dimple grinder. Final thinning was done in an Ar-ion mill. The TEM analysis was done on the JEOL 4000FX. Measurement of HBT layer thicknesses shown in Figs. 2 and 3 was in good agreement with the designed values.

Diffraction contrast was used in the TEM in order to image the different epilayers. All epilayers were grown on [001] GaAs substrates. Thus, the XTEM orientation for best contrast should be the [010] or [110] direction. The selected area diffraction pattern for the sample was recorded and indexed using JEOL 4000FX. After indexing, it was found that the zone axis for the sample was in the [110] direction. In order to obtain sufficient contrast between AlGaAs, InGaAs, and GaAs dark-field imaging using the intensity of the (200) reflection was used. It has been shown by the kinematical theory of electron diffraction that differences in the (200) correspond to differences in alloy content (Al or In) [11]. Under this theory, the intensity of the reflection is proportional to the square of the mass fraction of Al (atomic weight = 26.98) or In (atomic weight = 114.82). For the (200) dark-field image, GaAs appears grey, InGaAs black, and AlGaAs white.

Both samples showed very good regularity of crystalline structures. No defect was observed in the HBT layers from low and high-reliability wafers. The collector-base interface was transparent to XTEM since both layers are made from GaAs material. The emitter-base hetero-interface could, however, be clearly seen in the high-reliability wafer (Fig. 3) and appears to be sufficiently sharp. The low-reliability wafer, on the other hand, showed a fuzzy base-emitter hetero-interface, which suggests the presence of a graded Al profile in the emitter region of low-reliability HBTs in the vicinity of the hetero-interface. The presence of such a grading region was not expected according to the nominal design of the device and represents a possible reason causing the poor reliability characteristics on such material. Such grading may impact the dopant diffusion or mechanisms responsible for leakage currents and may affect the performance characteristics of low-reliability HBTs.

4. Photo-luminescence study of low- and high-reliability HBTs

Excitation-dependent PL can provide information on carrier life-time in the base and collector regions [15,16]. PL characterization of low and high-reliability HBTs at room temperature was performed to find the carrier lifetime in the base region. The top InGaAs emitter cap layer of both low and high-reliability wafers was removed to allow the luminescence emitted from the base and collector region to reach the detector, since InGaAs absorbs the wavelength of interest, due to its small bandgap. Fig. 4 shows the measured PL spectrum of low and high-reliability HBTs.

The luminescence from the low-doped ($\approx 5 \times 10^{15}$ cm^{-3}) GaAs collector region was observed at a wavelength of 8720 Å. This corresponds to a bandgap of

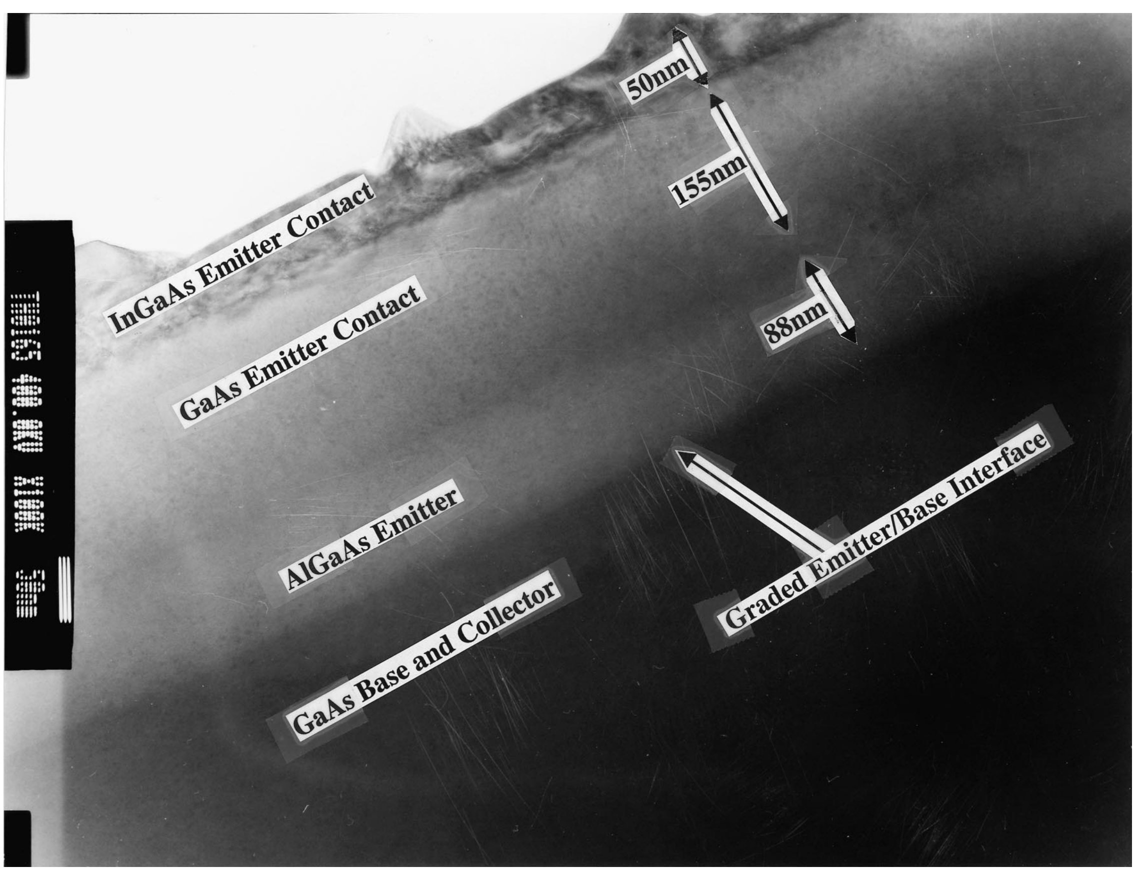

Fig. 2. XTEM picture of low-reliability wafer. The base-emitter hetero-interface appears to be a compositionally graded junction.

1.421 eV as expected for low-doped GaAs. The luminescence from the heavily doped ($\approx 1.5 \times 10^{19}$ cm^{-3}) base region occurred at a wavelength of 9000 Å. This corresponds to a bandgap of 1.377 eV and is higher than the expected values of 1.345 eV for this material calculated from $\Delta E_g = 2 \times 10^{-11}\ N_A^{0.5}$ for bandgap narrowing in P-type GaAs. The smaller bandgap observed in the GaAs base compared with the GaAs collector is due to the heavy doping of the base region with carbon.

The high-reliability HBTs in Fig. 4 show sharper PL peak with higher intensity for p$^+$ GaAs compared to low-reliability HBTs. This is due to the fact that the quality of the GaAs base material of low-reliability devices is inferior to that of high-reliability devices.

Study of the peak of the photo-luminescence vs the excitation density of the laser reveals the carrier lifetime in the base region as is depicted by the results of Fig. 5. The photo-luminescence intensity (PL) of the peak depends on the laser excitation density (I) according to the following relation [15].

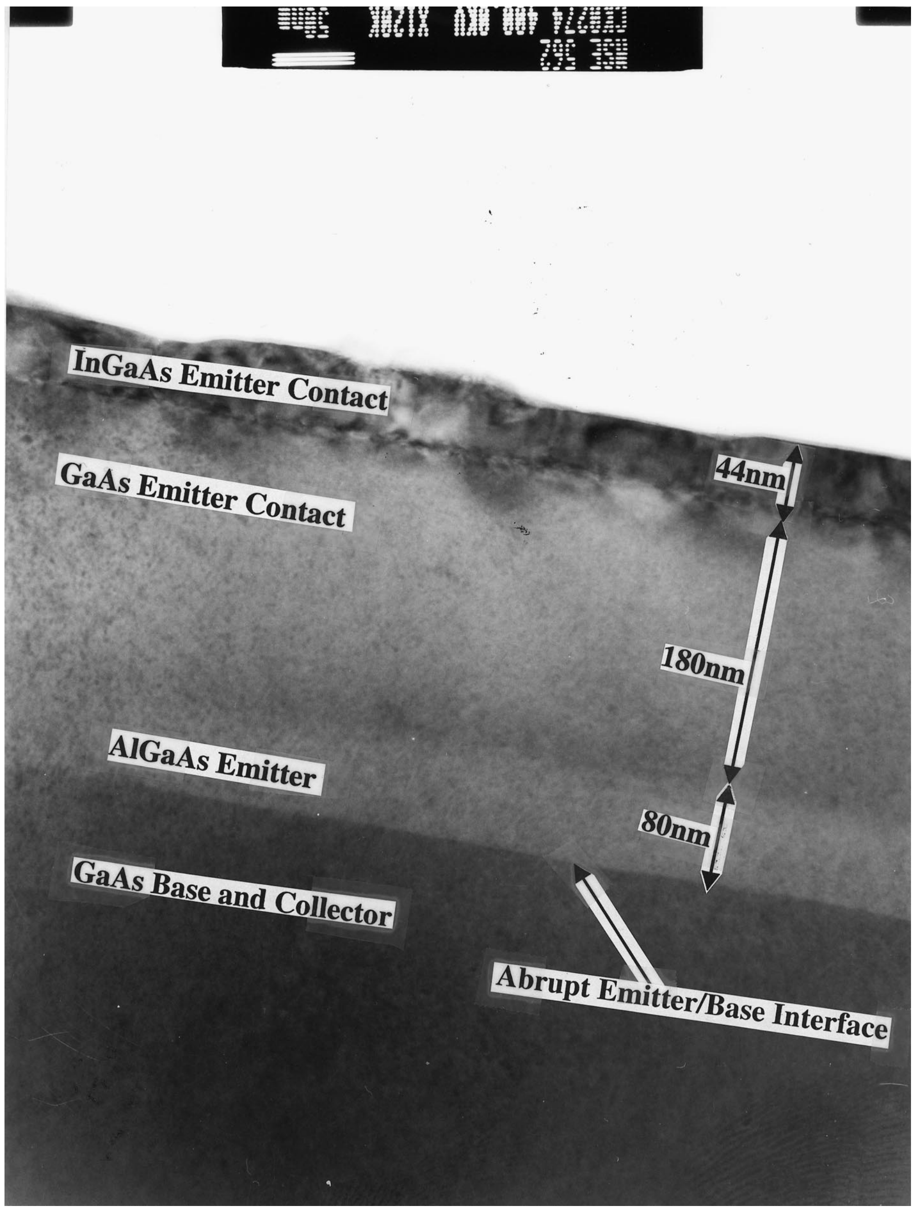

Fig. 3. XTEM picture of high-reliability wafer. The base-emitter hetero-interface appears to be an abrupt junction.

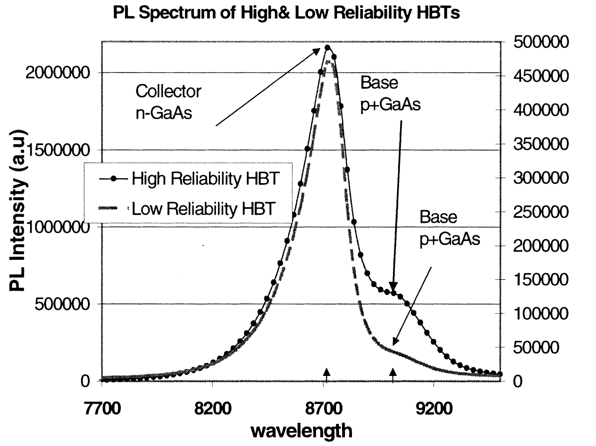

Fig. 4. PL spectrum of low and high-reliability HBTs. The InGaAs contact layer was etched away to allow observation of the PL from GaAs material.

$$PI = C_1 N\tau I + C_2\tau^{3/2} I^2 \quad (1)$$

where C_1 and C_2 are constants, N is the doping density and τ is the carrier lifetime. In the low-power excitation regime the increase in the photo-luminescence intensity (PL) is proportional to the laser excitation density (I) as shown by Eq. (1) and the results of Fig. 5. From this information, the carrier lifetime in the base may be found from the slope of the linear part of the curve of the PL density vs laser excitation density [15,16]. The deducted average carrier lifetime in the base of low and high-reliability HBTs was 60 and 150 ps, respectively. It appears, therefore, that trapping as manifested by reduced carrier lifetime characteristics leads to reduction of HBT reliability.

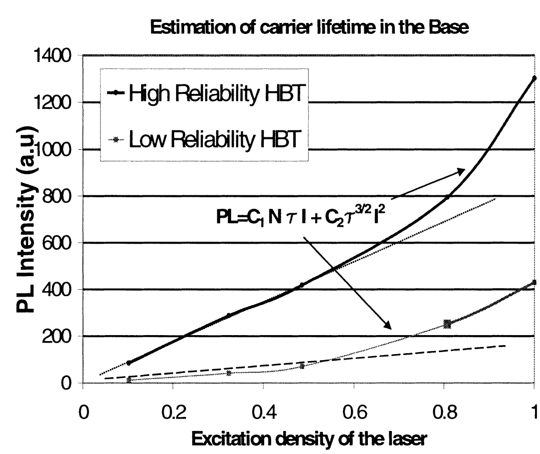

Fig. 5. The observed PL intensity of the P^+ GaAs material as a function of the laser excitation power. The PL intensity was recorded at the wavelength of 9000 Å.

5. Discussion

PL characterization of HBT layers points to a difference in the lifetime of minority carriers in the base of low and high-reliability devices (60 ps for low-reliability HBTs vs 150 ps for high-reliability HBTs). DC electrical characterization of HBTs fabricated on these layers showed identical gain characteristics. TEM analysis of the same samples showed no presence of defects in the crystalline structure in the active device region while the presence of a graded base-emitter junction was identified in low-reliability HBTs. High-reliability HBTs, on the other hand, show that their base-emitter junction is abrupt. Based on the above observations, one can discuss further the features of high and low-reliability HBTs as presented below.

In low-reliability HBTs, the inferior quality of the base region manifested by shorter carrier lifetime may also lead to an inferior quality of the base-emitter heterojunction which, combined with the detected presence of graded Al profile in the emitter, impacts the device reliability. High-reliability HBTs, on the other hand, present an abrupt base-emitter hetero-interface with a better quality of the base material compared to low-reliability devices. As a result, the gain of high-reliability HBTs is less influenced by base dopant out-diffusion compared to low-reliability HBTs. A higher defect density in the base region of low-reliability HBTs compared to high-reliability HBTs is another possible cause of performance degradation as also supported by the fact that the low-frequency noise in low-reliability HBTs is higher; a higher defect density in the base [18], as well as presence of a graded base-emitter hetero-interface, were found responsible for the low-reliability of these devices.

The above appears to agree with the report by Shin et al. who observed a degradation of the low-frequency noise performance of graded-junction AlGaAs/GaAs HBTs compared to the abrupt junction devices [19]. On the other hand, Chang et al. performed a theoretical analysis and concluded that abrupt-junction HBTs are more vulnerable to the change of current gain with base dopant out-diffusion compared to graded-junction devices [20]. The simulated HBT current gain and "minimum detectable dopant out-diffusion" vs grading length were used as criteria for the analysis. The minimum detectable dopant out-diffusion was used as a measure of sensitivity of the collector current to dopant out-diffusion. It was found that as the grading length in the emitter of the HBT increases, the current gain decreases, yet the device becomes less vulnerable to base dopant out-diffusion. This means that HBTs with graded Al profile in the emitter are less affected by dopant out-diffusion than abrupt-junction HBTs. Although this conclusion appears, at first glance, to contradict the results reported here, this is not the case as explained below.

All physical parameters such as doping concentration, carrier lifetime etc. considered in the theoretical analysis of HBT reliability [20] were assumed to be invariant and only the dopant can out-diffuse from base region to the emitter across the hetero-interface. The impact of graded vs abrupt junction base-emitter built-in field on the diffusion of dopants was also ignored. Moreover, the gain of the graded-junction HBT was smaller than that of abrupt-junction device, since a smaller valence band discontinuity is assumed for graded junction HBTs. The low and high-reliability HBTs studied in this work, on the other hand, showed identical gain characteristics, while other physical parameters such as the carrier lifetime in the base were different due to the fact that some variations in layer properties or interfaces between layers may have existed. Thus, a combination of factors such as dopant diffusion, but also carrier lifetime and hetero-interface sharpness need, to be considered in order to fully understand the material quality and device reliability.

A graded-heterojunction may also have poor reliability performance due to increased leakage current over the device operation time causing eventual device degradation. Another possible scenario for inferior reliability characteristics of graded heterojunction HBTs compared to abrupt heterojunction devices is enhanced dopant diffusion in graded-junction devices. The base dopant out-diffusion in graded-junction HBTs therefore results in an accelerated current gain degradation compared to abrupt-junction devices.

6. Conclusion

Overall, according to PL studies of carrier lifetime in the base of low and high-reliability HBTs, it appears that high-reliability HBTs are associated with better crystalline material quality compared to low-reliability devices. Combined with the formation of abrupt vs compositionally graded base-emitter hetero-interface evaluated by TEM analysis and also small low-frequency noise in high vs low-reliability HBTs, these studies set up device reliability evaluation criteria. Thus the combination of optical, structural and electrical characterization techniques permit prediction of device reliability.

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