Direct-Current Performance Improvements of Al_{0.45}Ga_{0.55}As/GaAs Digital Graded Superlattice-Emitter Heterojunction Bipolar Transistors by Wet-Oxidation

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Abstract

Heterojunction bipolar transistors (HBT’s) having an Al_{0.45}Ga_{0.55}As/GaAs digital graded superlattice (DGSL) emitter have been examined by wet-oxidizing the exposed portion of the emitter under various conditions. Such HBT’s with a high Al-fraction passivation layer exhibit a small offset voltage of 50 mV, a turn-on voltage of 0.87 V and a current gain of 385. Experimental results also reveal that the HBT’s with an exposed high Al-fraction emitter are sensitive to the ambient air. However, with InGaP capped upon the high Al-fraction emitter, the HBT’s exhibit better oxidation quality. The wet-oxidation brings forth the most remarkable improvements for the InGaP-capped HBT’s when the passivation layer is totally wet-oxidized.

1. Introduction

There have been lots of reports on heterojunction bipolar transistors (HBT’s) by using InGaP/GaAs and AlGaAs/GaAs material systems for both wireless and wired consumer applications [1]. For HBT’s, the key requirement to operate at low biased condition is to reduce the base-emitter (B-E) turn-on voltage ($V_{ON(B-E)}$). According to the newly reported results, it is found that a potential spike at the B-E junction still severely limits the reduction of $V_{ON(B-E)}$ even if a narrower band-gap base, such as InGaAs and/or In$_{x}$Ga$_{1-x}$As$_{y}$N$_{y}$, was used [2]. Therefore, extensive studies were on the elimination of a potential spike at either the B-E or the B-C heterointerface. They include a) HBT structure with an additional set-back layer [3], b) HEBT structure with separated carrier injection and confinement [4] and c) HBT structure with a delta-doped sheet [5].

Lee et al. have proposed an InGaAs/AlGaAs/GaAs quantum-well infrared photodetector (QWIP) using digital graded superlattice barriers (DGSLBs) to obtain the staircase-like graded barrier [6]. More recently, the authors of this paper have proceeded to demonstrate a novel HBT employing such a digital graded superlattice (DGSL) structure as part of the emitter to significantly reduce the base-emitter (B-E) turn-on voltage ($V_{ON(B-E)}$). Additionally, surface treatment in a furnace with vaporized H$_2$O was performed to investigate the effects of a high Al-fraction passivation layer on the device direct-current (DC) performances since the passivation layer with a high Al fraction exhibits a high oxidation activity.

2. HBT Structure and Fabrication

Fig. 1 is the schematic band diagram showing the conduction band and the valence band of an Al$_{0.45}$Ga$_{0.55}$As/GaAs DGSL structure investigated throughout this paper. It comprises four superlattice unit cell of four different barrier/well thicknesses (10/40, 20/30, 30/20 and 40/10 Å in sequence). Each of the four superlattice unit cells has a combination of 3 periods of Al$_{0.45}$Ga$_{0.55}$As/GaAs quantum wells.

The device structure was grown on a (100)-oriented GaAs substrate by metal-organic chemical vapor deposition (MOCVD) to comprise, from the substrate up, a 0.5-µm n+-GaAs sub-collector ($n_+ = 5 \times 10^{18}$ cm$^{-3}$), a 0.5-µm n--GaAs collector ($n_-=5 \times 10^{16}$ cm$^{-3}$), a 0.06-µm Al$_{0.45}$Ga$_{0.55}$As/GaAs DGSL emitter inserted between a 0.1-µm p+-GaAs base ($p_+ = 4 \times 10^{19}$ cm$^{-3}$) and a 0.04-µm n-InGaP sub-emitter ($n=5 \times 10^{17}$ cm$^{-3}$), and finally a 0.3-µm n+-GaAs cap layer ($n_+ = 5 \times 10^{18}$ cm$^{-3}$). The growth condition was published elsew [7].

The fabrication started with mesa isolation. The Al$_{0.45}$Ga$_{0.55}$As/GaAs DGSL layer was etched by using 1H$_2$SO$_4$:1H$_2$O$_2$:8H$_2$O solution at a etching rate of 210 Å/s [8]. Etching selectivity between GaAs (etched in 3NH$_4$OH:1H$_2$O$_2$:50H$_2$O) and InGaP (etched in 3NH$_4$OH:1H$_2$O$_2$:50H$_2$O) was employed throughout this work [9]. Then, both the cap and the InGaP layers were selectively removed during emitter mesa process [7].
AuGe was deposited to form the n-type ohmic contacts for the emitter and the collector simultaneously after the collector mesa step. Photo-resist was patterned to define the exposed base region, where AuZn was deposited to form the p-type ohmic contact for the base. Therefore, an HBT was formed to have a passivation layer composed of an InGaP layer and a DGSL layer (i.e., InGaP/DGSL-passivated HBT). The InGaP layer of the InGaP/DGSL-passivated HBT was then etched away to form a DGSL-passivated HBT.

To examine the effect of wet-oxidation on the studied devices, both the InGaP/DGSL-passivated HBT and the DGSL-passivated HBT were introduced into a chamber to proceed with multi-step wet-oxidation so that an InGaP/oxide-passivated HBT and an oxide-passivated HBT (i.e., oxide-passivated HBT1) were formed because the DGSL layer was oxidized due to the high amount of Al. The multi-step wet-oxidation process was performed using 100°C vaporized H2O as a gas source at a substrate temperature of 100°C for 20, 20+20 and 20+20+60 minutes, respectively. Furthermore, another oxide-passivated HBT (i.e., oxide-passivated HBT2) was fabricated when the InGaP layer of the InGaP/oxide-passivated HBT was etched away.

3. HBT Performances and Discussion

Fig. 2 shows the common-emitter characteristics of four HBT’s, where the base current $I_B$ is at a rate of 50 $\mu$A/step. An extremely small offset voltage of 50 mV is observed as shown in the inset. The small offset voltage of 50 mV is owing to the elimination of the potential spike that often appears at the B-E interface of the conventional HBT’s. As shown in Fig. 1, the $\Delta E_C$ associated with Al0.45Ga0.55As/GaAs is as high as 336 meV when no bias voltage is applied; however, in our newly designed emitter structure, the effective conduction band discontinuity at the B-E interface is reduced to less than 70 meV according to the calculation.

Fig. 3(a) shows the collector current $I_C$ and base current $I_B$ as a function of the base-emitter voltage $V_{BE}$ at a zero B-C voltage ($V_{BC}=0$ V) for these HBT’s. An important merit of the studied HBT’s is $V_{ON(B-E)}$, which is defined as $V_{BE}$ at which the collector current $I_C$ exceeds 1 $\mu$A. We find that these HBT’s exhibit nearly the same $V_{ON(B-E)}$ in the range of 0.85~0.87 V, which is about 250 mV lower than 1.12 V measured in a conventional Al0.45Ga0.55As/GaAs abrupt-emitter HBT. The collector ideality factor $\eta_c$ and the base ideality factor $\eta_b$ are 1.2 and 1.9, respectively. According to these values, the base current is mainly dominated by the recombination current in the B-E depletion region when $V_{BE}$ is small. It is noted that these HBT’s exhibit nearly the same base current at small $V_{BE}$ since these HBT’s use the same material for the base. However, as $V_{BE}$ increases, the base currents of the un-oxidized devices become significantly larger than those of the oxidized ones. This is due to the elimination of an induced built-in electric field in the passivation
layer after oxidation, which limits the parasitic current contributing to $I_B$. Particularly, when $V_{BE}$ rises up to, for example, 1.5 V, we find that the DGSL-passivated HBT exhibits the largest base current amongst the others, while the InGaP/oxide-passivated HBT the smallest. It is evident that, from the above base current trend, better base surface passivation results in a smaller base current. Briefly, the wet-oxidation treatment positively affects the studied devices. We also find that, however, wet-oxidation has almost no effect upon $I_C$. Note that the DGSL-passivated HBT has the largest collector current when $V_{BE}$ is large, which indicates the removal of the InGaP cap layer increases the collector current when there is an induced built-in electric field. However, as shown in Fig. 3(b), the same phenomenon does not appear when the InGaP layer of the InGaP/oxide-passivated HBT is removed (namely, oxide-passivated HBT2). It is because there is no more built-in electric field in the oxide layer. Furthermore, the $I_B$ of the oxide-passivated HBT2 is smaller than that of the oxide-passivated HBT1, which indicates that wet-oxidation with a capped InGaP layer results in better oxide quality.

In Fig. 4, a more detailed discussion is given on the current gains as a function of the collector current. We first consider the un-oxidized devices (the InGaP/DGSL-passivated HBT and the DGSL-passivated HBT). At small $V_{BE}$ (where $I_C$ is small), the base current is dominated by the bulk recombination current within the B-E depletion region, which is much larger than the hole back-injection current. With the increase of $V_{BE}$, the B-E depletion width gets narrower, resulting in a reduced recombination current and hence an enhanced current gain. We find that the current gains for both the un-oxidized HBT’s monotonically increase when $I_C$ is relatively small. Further increasing $V_{BE}$, the base current should be dominated by the back-injection current and the current gain should maintain at a fixed value over a wide $I_C$ range. However, we still observe an increasing current gain rather than a constant value. This abnormal behavior is explained by introducing a concept of built-in electric field within the 600-Å graded emitter.

As shown in Fig. 1, some $V_{BE}$ being large enough will lead to a negligible depletion region in the B-E junction. In this case, a nearly flat-band condition for the graded emitter is established and a built-in electric field is also naturally induced along both the conduction and the valence bands. This built-in electric field along valence band successfully pushes the holes back to the base region, resulting in a much lower base current as compared to a normal back-injection current. Therefore, we obtain a current gain as high as 385 for the DGSL-passivated HBT. It is noted that the current gain of the InGaP/DGSL-passivated HBT becomes smaller than that of the DGSL-passivated HBT when the collector current exceeds 1 mA.

For the oxidized devices (the InGaP/oxide-passivated HBT, the oxide-passivated HBT1 and the oxide-passivated HBT2), the base current of the oxidized devices is equal to that of the un-oxidized ones when $V_{BE}$ is small. When $V_{BE}$ rises up to, for example, 1.1 V, however, the base current of oxidized devices becomes smaller than that of the un-oxidized ones. It is believed that better surface passivation is achieved by wet-oxidizing the passivation layer (namely, the DGSL layer or the InGaP/DGSL layer). As $V_{BE}$ increases further to, for example, 1.5 V, the base current of the InGaP/oxide-passivated HBT becomes even smaller than that of the oxide-passivated HBT1, which implies that the InGaP sub-emitter provides better oxidation quality. Moreover, if we demonstrate the gain as a function of the collector current, the oxidized devices always exhibit a higher value than that of un-oxidized ones. More particularly, the gain of the oxide-passivated HBT2 is higher than that of the oxide-passivated HBT1, which is consistent with the results shown in Fig. 3.

To further investigate the effects of the oxidized passivation layer upon the output characteristics, the DGSL-passivated HBT was introduced into a chamber with vaporized H$_2$O to proceed with multi-step wet-oxidation. Fig. 5 shows the measured collector currents as a function of the wet-oxidation time with the base current as a parameter.

![Figure 4](image1.png)  
**Figure 4** The current gains as a function of the collector current.

![Figure 5](image2.png)  
**Figure 5** The measured collector currents of the oxide-passivated HBT1 as a function of the wet-oxidation time with the base current as a parameter.
We find that the collector currents decrease after the first- and the second-step treatments as compared with those without oxidation. Whereas, enhanced collector currents were obtained after finishing the third-step treatment. There are a parasitic current path for electrons through passivation layer (resulting in a parasitic electron current, \( e_P \)) and a built-in electric field along the conduction band, which are functions of the B-E bias and are also denoted in this figure. In region I of Fig. 5, the base current (i.e., \( V_{BE} \)) is small and the passivation layer is partly oxidized. The \( e_P \) is blocked due to the oxidized passivation layer. However, the \( e_P \) reduction is insignificant since the original \( e_P \) contributes little to \( I_C \) due to the negligible built-in electric field and the lack of current path at this small \( V_{BE} \). Therefore, we observe time-insensitive collector currents after the first- and the second-step treatments. The base current (\( V_{BE} \)) in region II increases so that an enhanced electric field is constructed along with a parasitic current path. An available parasitic electron current contributing to the collector current is expected before the passivation layer is entirely oxidized. This is why a remarkable reduction in the collector current after the first- and the second-step treatments is observed in region II. On the other hand, it is believed that most of the passivation layer is wet-oxidized in regions III and IV after the third-step treatment. Thus the built-in electric field within the passivation layer no more exists. We clearly find that current enhancement instead of current reduction occurs in both regions III and IV. In region IV, the output collector currents are even larger than those before wet-oxidation. This performance improvement is owing to better surface passivation resulting from the wet-oxidized AlGaAs/GaAs superlattice.

Figure 6: The measured collector currents of the InGaP/oxide-passivated HBT as a function of the wet-oxidation time with the base current as a parameter.

Compared with the oxide-passivated HBT1, the InGaP-capped device (the InGaP/oxide-passivated HBT) shows better oxidation quality. As a result, the phenomenon in region II in Fig. 5 does not appear in Fig. 6. In other words, the better surface passivation is, the smaller base current we obtain. Since the collector current is measured with the base current fixed, a higher \( V_{BE} \) bias is needed to maintain this base current, resulting in a larger collector current. This phenomenon can also be observed in Fig. 4 where different \( V_{BE} \) biases are needed to obtain the same base current level before oxidation and after complete oxidation. This is why the oxidized HBT’s exhibit smaller current gains at some \( V_{BE} \) but higher current gains at some collector current as compared with the oxidized HBT’s.

4. Conclusion

Various Al\(_{0.45}\)Ga\(_{0.55}\)As/GaAs DGSL-emitter heterojunction bipolar transistors have been compared and investigated. Such HBT’s with a high Al-fraction passivation layer exhibit a small offset voltage of 50 mV, a turn-on voltage of 0.87 V and a current gain of 385. To study the effects of a high Al-fraction passivation layer on device performances, surface treatment by wet-oxidation process was employed. Experimental results also reveal that the HBT’s with an exposed high Al-fraction emitter are sensitive to the ambient air. However, with InGaP capped upon the high Al-fraction emitter, the HBT’s exhibit better oxidation quality. The wet-oxidation brings forth the most remarkable improvements for the InGaP-capped HBT’s when the passivation layer is totally wet-oxidized.

5. References