AlGaAs/GaAs HBTs with C-doped base and undoped emitter-base spacer layer

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Abstract Effect of undoped GaAs spacer layer between AlGaAs emitter layer and C-doped GaAs base layer on DC characteristics of AlGaAs/GaAs HBTs with ledge structure was investigated. Devices with spacer layer thickness (~3-5 nm) and optimal ledge geometry demonstrate stable high current gain ($\beta_{\text{max}} = 120-140$) combined with collector-emitter breakdown voltage of 23-25V.

1. Introduction
Heterojunction bipolar transistors (HBTs) are widely used as microwave power devices due to their intrinsic high-power density, linearity and efficiency [1]. Initially beryllium (Be) was used as an p-dopant for GaAs base layers in AlGaAs/GaAs HBT epitaxial structures. However it is difficult to provide high p-doping level due to Be surface segregation and diffusion in GaAs and AlGaAs layers grown by molecular beam epitaxy (MBE) [2]. To prevent negative effect of uncontrollable Be redistributing the thin undoped GaAs spacer layer may be introduced between n-doped AlGaAs emitter layer and p-doped GaAs base layer but it is not guarantee long-term reliability at high current density and high temperatures [3]. Therefore, currently carbon (C) is widely used in MBE for p-doping due to its low diffusion coefficient and high solubility in GaAs layers [4].

It is well known that high surface recombination velocity for highly doped p-type GaAs base layers leads to degradation of the HBT current gain. The insertion of a thin depleted layer with a wide band gap and a low surface recombination velocity over the extrinsic base region around the emitter periphery (so called ledge) is an effective approach for recombination current reduction. Using a depleted ledge over the extrinsic base surface improve gain stability [5], device reliability [6] and significantly reduce l/f noise of AlGaAs/GaAs HBT’s [7].

Proper ledge design is critical since thick or heavily doped ledge as well as too thin or lightly doped one may result in degradation of initial DC characteristics and poor device reliability. In C-doped GaAs HBTs n-doped emitter and p-doped base usually are in direct contact without any spacer layer between them [8]. Although the insertion of undoped GaAs layer between emitter and base can improve the ledge passivation effectiveness, it may also reduce emitter efficiency simultaneously. In this paper, we investigate effect of undoped GaAs spacer thickness on DC characteristics of C-doped AlGaAs/GaAs HBTs.
2. Results and discussion

The layer sequences of HBT epitaxial structures under investigation are given in Table 1. Thin undoped GaAs spacer layer separates n-doped AlGaAs emitter layer with graded interfaces from C-doped p-GaAs base layer. Cross-section of HBT emitter-base region is schematically shown in Figure 1. Ledge structure includes bottom undoped GaAs part and top n-doped AlGaAs part. The ledge length can be roughly estimated as distance between emitter mesa edge and base contact.

| Layer     | Material      | Thickness (nm) | Doping (cm$^{-3}$), dopant |
|-----------|---------------|----------------|----------------------------|
| Cap       | n$^+$ InGaAs/GaAs | 10             | >5x10$^{18}$, Si           |
|           | gradient n AlGaAs | 30             | gradient, Si               |
| Emitter   | n Al$_{0.25}$Ga$_{0.75}$As | 80             | 5x10$^{17}$, Si            |
|           | gradient n AlGaAs | 20             | 5x10$^{17}$, Si            |
| Spacer    | u.d. GaAs     | 0-10           | -                          |
| Base      | p GaAs        | 80             | 2x10$^{19}$, C             |
| Collector | n GaAs        | 700            | 2x10$^{16}$, Si            |
| Sub-collector | n$^+$ GaAs       | 600            | 3x10$^{18}$, Si           |
| Buffer    |               | 200            | -                          |

Table 1. Epitaxial layers structures parameters of investigated HBTs.

Figure 1. Schematic cross-section of HBT around the emitter ledge.

The numerical modeling of HBTs with the emitter mesa width of 4 µm and the ledge length of 3 µm was carried out. Figure 2 depicts the calculated dependences of the current gain $\beta$ on the total ledge thickness for different thickness of undoped GaAs spacer layer. On the one side, for the fixed thickness of undoped GaAs spacer layer, the increase in the total ledge thickness leads to the reduction of the surface recombination at the ledge (due to higher Al composition at the ledge surface) and, as a result, the rise of the current gain. When the total ledge thickness becomes greater than the depth of the surface depletion region, the electron concentration in the ledge increases (see Figure 3), which leads to the increase in the effective emitter width and increasing of the current gain. However, increased effective emitter width leads to significant growth of the emitter-base capacity and RF characteristics degradation. Therefore the total ledge thickness (including bottom undoped GaAs and top n-doped AlGaAs parts) is optimal when the ledge area is nearly full depleted and the surface recombination is damped. In our case optimal total ledge thickness is roughly about 5-10 nm (depending on the undoped GaAs spacer thickness).

On the other side, for the fixed ledge thickness, the increase in the thickness of undoped GaAs spacer layer leads to the rise of the surface recombination at the ledge (due to lower Al composition at the ledge surface) and, as a result, the reduction of the current gain (see Figure 2). However the high-
power HBT’s undergoes significant heating and thermal cycling during operation. Therefore the decrease in the chemical activity of the surface layer due to the reduction of the Al composition (<15%) should lead to the improvement of the device reliability and life-time.

![Diagram](image)

**Figure 2.** Calculated current gain as a function of total ledge thickness for different spacer thickness. The solid lines correspond to the fixed Al composition on the ledge surface.

![Diagram](image)

**Figure 3.** Calculated 2D distributions of electron concentration at $I_C = 3.6$ mA/µm for HBTs based on the epitaxial structure with 3-nm-thick spacer layer and 8 nm-thick (a) and 25 nm-thick (b) ledge thickness.
According with modeling results the maximum current gain $\beta_{\text{max}} \approx 150$ as well as better surface passivation and stability can be achieved when the thickness of undoped GaAs spacer layer is about 3-5 nm. Experimental device fabrication included the following basic steps: emitter contact deposition, emitter mesa etching down to the ledge surface, ledge mesa etching down to the base layer and base contact deposition, base mesa etching down to the sub-collector layer and collector contact deposition, isolation mesa etching down to substrate, dielectric passivation, contact pad deposition, emitter air bridge formation. To obtain the optimal ledge thickness the etching depth of the emitter mesa was controlled by measurement of leakage current between neighboring emitter contacts.

The effect of the surface recombination in the ledge can be neglected in HBTs with large emitter size. Test HBTs with emitter size $\sim 50 \times 100 \, \mu m$ based on the epitaxial structures with undoped GaAs spacer thickness of 10, 5 and 0 nm demonstrate the maximum current gain $\beta_{\text{max}}$ of about 200, 240 and 315, respectively. It is clearly indicated that the thicker undoped GaAs spacer layer results in the emitter efficiency degradation.

In case of HBTs based on the epitaxial structure without any undoped GaAs spacer layer, the devices with the emitter mesa width of 4 $\mu$m and the ledge length of 3 $\mu$m demonstrate the current gain $\beta_{\text{max}}$ in the range of 90-150. According to the numerical modeling results, the obtained high dispersion of DC characteristics can be attributed to the strong impact of the ledge thickness on the current gain. Moreover, the lower experimental value of the maximum current gain as compared to the calculated data can be attributed with the partial oxidation of the ledge surface (typical oxidation depth is 2-4 nm depending on the Al composition) which reduces the effective ledge thickness. At the same time, HBTs based on the epitaxial structure with 5 $\mu$m-thick undoped GaAs spacer layer and the same device geometry demonstrate the more uniform distribution of the maximum current gain from chip to chip ($\beta_{\text{max}} = 120-140$). The collector-emitter breakdown voltage of 23-25V was obtained for all investigated HBTs. Such combination of high current gain and reasonable breakdown voltage is suitable for most RF applications.

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