Explanation of Anomalously High Current Gain Observed in GaN Based Bipolar Transistors

H. Xing, D. Jena, M. J. W. Rodwell, and U. K. Mishra

***Abstract*—The potential applications of GaN-based bipolar transistors have suffered a setback from poor ohmic contacts and leakage currents. We show in this work that the extrinsic current gain β_{EXT} measured at a low current level can be erroneously attributed to the gain of the intrinsic transistor. By accounting for leakage current coupled with poor ohmic contacts, we show that the observed very high β_{EXT} at low current levels can be modeled accurately. The real gain of the intrinsic transistor β_{INT} is generally much lower. As the current is increased, the effect of leakage currents is diminished, and $\beta_{\mathrm{EXT}} \rightarrow \beta_{\mathrm{INT}}$. This model is satisfactorily applied to explain our experimental results.**

***Index Terms*—Bipolar transistors, common emitter, current gain, GaN, Gummel plot, HBT, leakage currents.**

I. Introduction

THE DEVELOPMENT of GaN-based bipolar transistors and related materials is an important objective due to its potential advantages of handling high-power density and operating under harsh and high temperature conditions. Both n-p-n and p-n-p GaN-based bipolar transistors have been reported using various techniques including base regrowth, emitter regrowth, direct mesa etch, and p-InGaN-base [1]–[4].

Due to Schottky-like ohmic contacts on p-GaN, its low conductivity, and high leakage paths resulting from dislocations in materials and processing, it has been difficult to obtain working bipolar transistors [5]. From common emitter operation and Gummel plot, current gain β varying from 3 up to 100 has been reported [4], [6]–[12]. However, it is commonly seen that high β can only be obtained with a collector current smaller than 1 mA (a corresponding average current density of $\leq$100 A/cm^2) [9], [11]–[13] and that sometimes, β exhibits a very high peak at low current level in the microamp range [8], [14], [15]. To understand these issues and characterize devices correctly, we carefully studied the impact of poor ohmic contacts and leakage currents I_{CBO} and I_{CEO} on the measured device performance, especially on the Gummel plot. This paper seeks to explain the high current gain at low current levels widely observed in GaN-based bipolar transistors and suggests ways to extract intrinsic device performance properly.

Manuscript received September 5, 2002; revised November 4, 2002. This work was supported by the Office of Naval Research Compact Power Supplies MURI program under the supervision of J. Zolper and H. Dietrich. The review of this letter was arranged by Editor D. Ritter.

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Digital Object Identifier 10.1109/LED.2002.807023

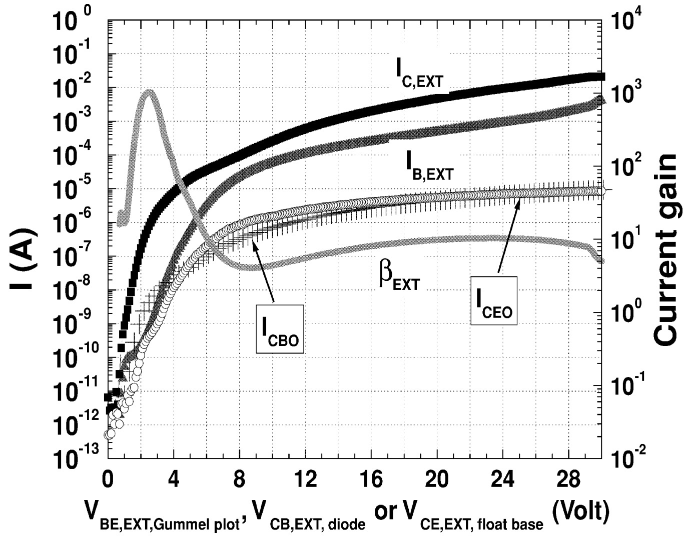

Fig. 1. Gummel plot of an $Al_{0.06}$GaN/GaN n-p-n HBT with $V_{BC,EXT} = 0$ V, along with leakage currents I_{CBO} and I_{CEO}.

II. Simulation Considerations

Commercial software advanced design system (ADS) was used to simulate dc device performances. For the purpose of a conceptual demonstration, we adopted the built-in model for n-p-n Si bipolar transistors (BJTs), which is modified from the integral charge control model of Gummel and Poon. The parameters were otherwise set at default values with a maximum forward current gain of 10.

III. Results and Discussions

Fig. 1 shows an example of an experimentally measured Gummel plot, where the emitter–base junction was biased with base and collector electrodes shorted ($V_{BC,\mathrm{EXT}} = 0$ V). The device under measurement is an $Al_{0.06}$GaN/GaN n-p-n heterojunction bipolar transistor (HBT) with an emitter size of 20×50 μm [16]. For reference, the reverse-bias collector–base leakage current I_{CBO} and the collector–emitter leakage current I_{CEO} measured on the same device are also plotted in Fig. 1. Noticeable in the plot is the high applied $V_{BE,\mathrm{EXT}}$ of $\sim$30 V in order to achieve a decent collector current of $\sim$20 mA. This results from poor ohmic contacts and high base resistance, which are confirmed by transmission line method (TLM) measurements, and the base contacts are found to be Schottky-like. At a low current level, both measured collector current $I_{C,\mathrm{EXT}}$ and base current $I_{B,\mathrm{EXT}}$ increase rapidly with increasing $V_{BE,\mathrm{EXT}}$. However, it is not possible to determine

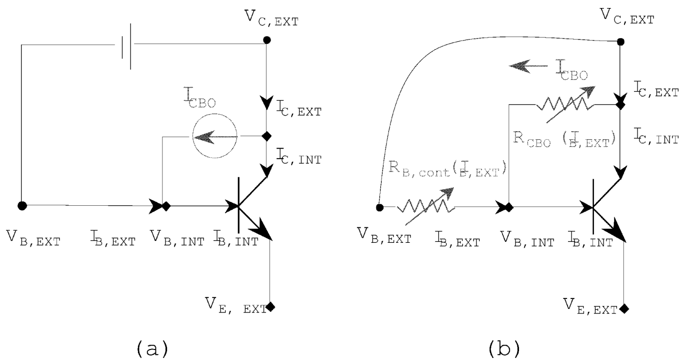

Fig. 2. Simplified circuit diagrams for relationships between terminal currents (a) With a finite I_{CBO} introduced by reverse-biased base–collector junction. (b) With a Schottky-like base contact and a varying I_{CBO} represented by two variable resistors $R_{B,\,cont}$ $(I_{B,\,\text{EXT}})$ and R_{CBO} $(I_{B,\,\text{EXT}})$, respectively.

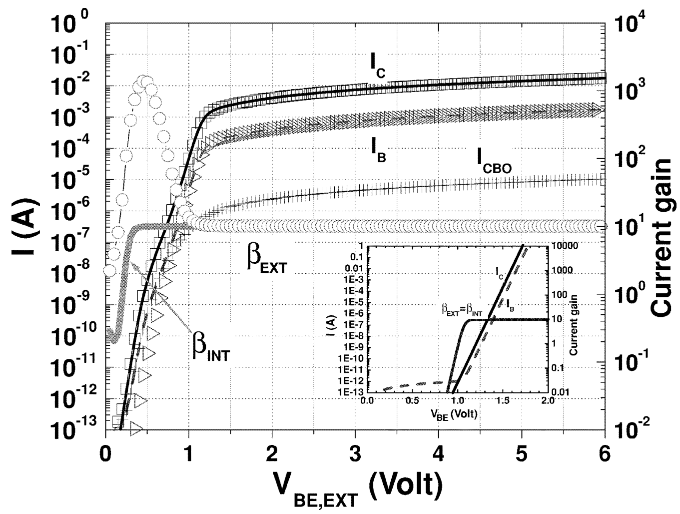

Fig. 3. Simulated Gummel plot of a classical Si BJT with a poor base contact and a high base–collector leakage path according to the simplified circuit diagram in Fig. 2(b). Lines represent the intrinsic device performance, and symbols represent the extrinsic device performance. The inset shows the simulated Gummel plot of the ideal BJT used.

the ideality factor of the intrinsic junctions because of the prevailing leakage currents. When $I_{B,\,\text{EXT}}$ increases beyond 20 μA, the change in the slope of currents versus $V_{BE,\,\text{EXT}}$ indicates that the high base resistance becomes dominant relative to the junction resistance.

The measured current gain $\beta_{\text{EXT}} = I_{C,\,\text{EXT}}/I_{B,\,\text{EXT}}$ exhibits a huge peak around $V_{BE,\,\text{EXT}} \sim 2.5$ V, and similar dc characteristics have been observed by other groups as well [8], [14]. Following a minimum around 8 V, β_{EXT} continues to increase and then saturates around 8–10 in a collector current range of 2∼20 mA before it decreases rapidly. The decrease in current gain at the high current level is due to the onset of the Kirk effect [16]. Due to the high base sheet resistance (∼100 kΩ/square), the emitter crowding effect is extremely severe. For our device, the effective active emitter area is estimated to be less than 1% of the total emitter area at a base current higher than 1 mA, adopting the concept of the effective emitter width from [17], [18]. Although the average current density is only 2 kA/cm^2 at an output current of 20 mA, the effective emitter current density at the emitter finger edge is estimated to be higher than 100 kA/cm^2.

Classically anomalous current gain has been observed due to a finite I_{CBO} [17]. Fig. 2(a) depicts a simplified circuit diagram showing the relationship between various terminal currents in the presence of a finite I_{CBO} introduced by applying a reverse bias across base–collector junction. The currents are defined to be positive when flowing into the device terminals. We can write

$$\begin{aligned} I_{C,\,\text{EXT}} &= I_{C,\,\text{INT}} + I_{\text{CBO}} \\ &= \beta_{\text{INT}} \cdot I_{B,\,\text{INT}} + I_{\text{CBO}} \qquad (1) \\ I_{B,\,\text{EXT}} &= I_{B,\,\text{INT}} - I_{\text{CBO}} \qquad (2) \\ \beta_{\text{EXT}} &= \frac{I_{C,INT} + I_{\text{CBO}}}{I_{B,\text{INT}} - I_{\text{CBO}}} \\ &= \beta_{\text{INT}} \cdot \frac{I_{B,\text{EXT}} + I_{\text{CBO}} + I_{\text{CBO}}/\beta_{\text{INT}}}{I_{B,\text{EXT}}} \qquad (3) \end{aligned}$$

where $I_{C,\,\text{INT}}$, $I_{B,\,\text{INT}}$, and β_{INT} are the collector current, base current, and current gain of the intrinsic device, respectively. Obviously, when $V_{BE,\,\text{EXT}}$ is small so that $I_{B,\,\text{INT}}$ is still smaller than I_{CBO}, the measured base current $I_{B,\,\text{EXT}}$ is practically negative. β_{EXT} goes to infinity and changes sign when $I_{B,\,\text{INT}}$ approaches I_{CBO}.

A Gummel plot is therefore normally taken with base and collector shorted to minimize influences from I_{CBO} or impact ionization in the collector. If the ohmic contacts of base and collector are perfect, the intrinsic base–collector junction can indeed be able to maintain close to zero bias. However, in the case of GaN-based bipolar transistors, base contacts of n-p-n are normally Schottky-like, and the base–collector leakage current is high. In a typical Gummel plot configuration with external base and collector electrodes shorted, the base–collector junction becomes further reverse biased when $I_{B,\,\text{EXT}}$ increases with increasing $V_{BE,\,\text{EXT}}$ due to the increasing voltage drop across the Schottky-like ohmic contacts and series resistance.

The simplified circuit diagram neglecting base sheet resistance is plotted in Fig. 2(b), where two nonlinear variable resistors $R_{B,\,cont}$ and R_{CBO} denote the leaky Schottky diode nature of base contacts and the leaky base–collector junction, respectively. Equations (1)–(3) still hold for the relationship between various terminal currents, except that I_{CBO} becomes dependent on $I_{B,\,\text{EXT}}$ since the voltage drop across the base contact $V_{B,\,cont} = V_{B,\,\text{EXT}} - V_{B,\,\text{INT}}$ is equal to the reverse bias induced on the intrinsic base–collector junction. According to (3), β_{EXT} can be falsely increased depending on the relative magnitude of I_{CBO} with respect to $I_{B,\,\text{EXT}}$ at the same $V_{B,\,cont}$. For instance, assume $I_{\text{CBO}} \cong I_{B,\,\text{EXT}}$ and a β_{INT} of 0.1 β_{EXT} is calculated to be 1.2. Due to I_{CBO} coupled with poor ohmic contacts, measured data shows a higher-than-unity current gain on a device that has no current gain at all. Application of voltage $V_{BE,\,\text{EXT}}$ necessitates a voltage division between $R_{B,\,cont}$ and the base–emitter junction. Thus, $I_{B,\,\text{EXT}}$ is forced to be always positive and cannot become negative, as discussed in the classical scenario. Therefore, β_{EXT}, in this case, does not change sign.

Fig. 3 displays a Gummel plot of an Si BJT simulated by ADS with two nonideal elements depicted in Fig. 2(b): $R_{B,\,cont} = (1 - \tanh((V_{BE,\,\text{EXT}} - 0.2)/0.1)) \cdot 3 \times 10^{11} + 3000\ \Omega$ and $R_{\text{CBO}} = 5 \times 10^{10} \cdot (V_{BE,\,\text{EXT}} + 1)^{-16} + 5 \times 10^5\ \Omega$. The empirical values of $R_{B,\,cont}$ and R_{CBO} are chosen in such a way so that the Schottky-like base contact with $V_{turn\text{-}on} \sim 0.3$ V can be modeled and a similar shape of a Gummel plot to our experimental result is generated. In Fig. 3, the solid lines and the lines with symbols represent simulated values of the intrinsic and extrinsic devices, respectively, and $I_{\rm CBO}$ is also plotted against $V_{BE,\,\rm EXT}$. The inset shown in Fig. 3 is the Gummel plot of the ideal transistor used, whose $I_{B,\,\rm INT}$ is dominated by the space charge recombination current at a low current level. It is very clear that at a low current level, the presence of $I_{\rm CBO}$ pushes up $I_{C,\,\rm EXT}$ while pushing down $I_{B,\,\rm EXT}$, resulting a high peak in $\beta_{\rm EXT}$, whereas $\beta_{\rm INT}$ behaves as expected. As the current increases, $I_{\rm CBO}$ becomes substantially smaller than $I_{B,\,\rm EXT}$ (two orders lower beyond $V_{BE,\,\rm EXT} \sim 2$ V); therefore, $\beta_{\rm EXT}$ drops back to $\beta_{\rm INT}$. Depending on the forms of $R_{B,\,cont}$ and $R_{\rm CBO}$ in the simulation, it can also be shown that $\beta_{\rm EXT}$ sometimes exhibits a plateau in the low current region rather than a peak. The anomalous current gain generally appears below the external turn-on voltage of the base–emitter junction, where injected current levels are still low. This explains the difference of $V_{BE,\,\rm EXT}$ observed at $\beta_{\rm EXT}$ peak in the simulation using Si BJT (~0.5 V) and our GaN HBT (~2.5 V).

Our simulation suggests that due to poor ohmic contacts and leaky base–collector junctions, $\beta_{\rm EXT}$ can be much higher than $\beta_{\rm INT}$, which can lead to erroneous analysis of the intrinsic GaN-based transistors, such as estimation of minority carrier lifetime in the base. It also suggests that the intrinsic device performance can only be measured when the influence from leakage currents is negligible. Although not specially addressed, $I_{\rm CEO}$, which also contributes to $I_{C,\,\rm EXT}$ and hence anomalous $\beta_{\rm EXT}$, is relatively small in our transistors, as is apparent in Fig. 1. Thus, the logic of this paper is not affected by neglecting this. When the leakage currents $I_{\rm CBO}$ and $I_{\rm CEO}$ are at least one order of magnitude lower than $I_{B,\,\rm EXT}$, for our device, the measured $\beta_{EXT} = \beta_{\rm INT}$ ~8–10 for $I_{C,\,\rm EXT} = I_{C,\,\rm INT}$ ~2–20 mA. In fact, this analysis can be largely generalized to guide proper characterization of bipolar transistors based on other materials as well, where high parasitic resistance and leakage currents are problems.

The Gummel plot is used in the analysis to show the impact of poor ohmic contacts coupled with high leakage paths. It can be shown that the same mechanism can lead to an anomalously high $\beta_{\rm EXT}$ at a low current level from common emitter characterization as well. Although the discussion above is focused on n-p-n bipolar transistors, it is straightforward to extend the analysis to p-n-p GaN-based transistors, where the ohmic contacts are poor for the collector rather than the base, along with high leakage base–collector path.

IV. Conclusion

We have proposed that the common problematic ohmic contacts and leaky base–collector junction in GaN-based bipolar transistors can result in an anomalously high current gain at a low current level, which can lead to erroneous conclusions on the intrinsic device performance. A simple circuit model accounting for the poor base contacts coupled with the leaky base–collector junction is presented, which captures the high $\beta_{\rm EXT}$ obtained in Gummel plots. The correct intrinsic device gain has to be determined at a high current level, where the leakage currents are negligible.

Acknowledgment

The authors would like to thank L. McCarthy for fruitful discussions.

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