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Substrate Parasitic Current in InGaP/GaAs HBTs

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1. Introduction

InGaP/GaAs heterojunction bipolar transistors (HBTs) exhibit excellent performance in high-speed and microwave applications. The semi-insulating GaAs substrate significantly reduces parasitic effects, and is usually considered non-conducting. Therefore, substrate leakage current is rarely studied, and the current paths are usually neglected in device models. In our measurement, however, we found that the collector and base currents vary with substrate bias. In this work, characteristics in the substrate-subcollector junction and current transport mechanism in substrate are investigated. The effect of substrate thickness will be addressed.

2. Measurement and Simulation

The collector current measured as a function of base-emitter bias is shown in Fig. 1. The substrate thickness of the HBT is 100 μm. Three substrate biases (Vs) with respect to collector were used: 0, +2V, and −2V. When Vs is −2V, the low-level collector current is increased to nearly 10^{-8} A. On the other hand, when Vs is +2V, the low-level collector current becomes negative.

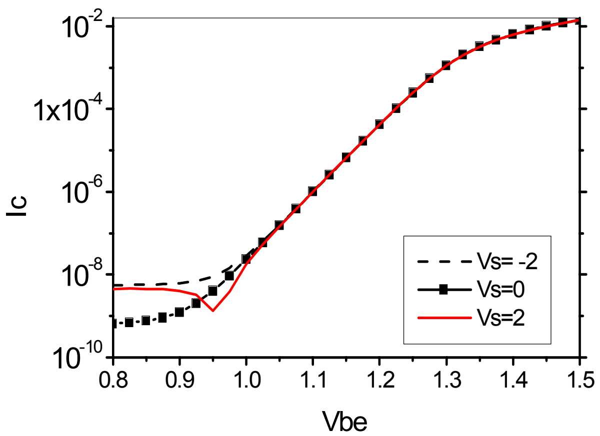

Fig. 1: Measured collector current at different substrate biases (Vs). $V_B = V_C = 0$.

The current transport at substrate-subcollector junction can be visualized as a p^--n^+ junction [1]. However, since the substrate is intrinsic, the forward and reverse currents are different from a normal pn junction. Fig. 2 shows the measured current as a function of Vs, with collector biased at 0V. While the forward current does not increase as fast as a pn junction, the reverse current has a linear dependence on bias, which is not typical in a pn junction. If the linear component is subtracted from the entire biasing range, the remaining component is zero in reverse bias (as expected), but becomes parabolic in forward bias region. As shown in Fig. 2, the measured forward current can be decomposed into a linear component (determined from reverse current) and a non-linear component. The latter can be fitted with a parabolic curve. Therefore, the substrate-subcollector junction forward current is in the form of

$$Is = A \cdot Vs + B \cdot Vs^2 \tag{1}$$

A and B are constants. The first term in eq. (1) is present in forward and reverse biases, whereas the second term is present in forward bias (Vs > 0) only. To identify the origin of the forward current components, Medici is used to calculate the current in substrate-subcollector junction, as shown in Fig. 3. The simulated reverse current is very small, unlike the linear behavior in measured result. In addition, the simulated forward current does have a parabolic nature. So we can conclude that the linear component in measured current is not associated with the junction itself; it is originated from other leakage paths. The parabolic component in forward bias will be discussed next.

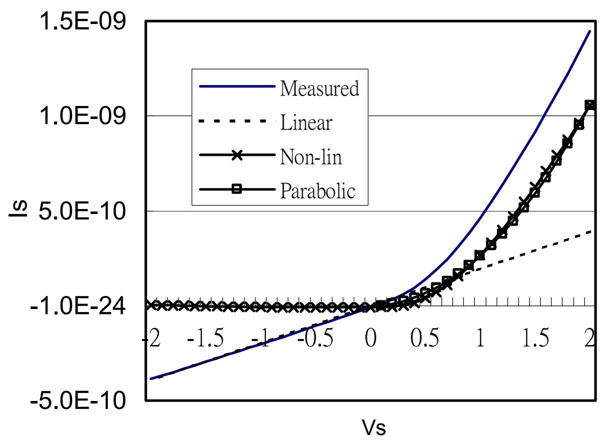

Fig. 2: Measured substrate-subcollector junction current, and its linear/nonlinear components. Emitter and base are open.

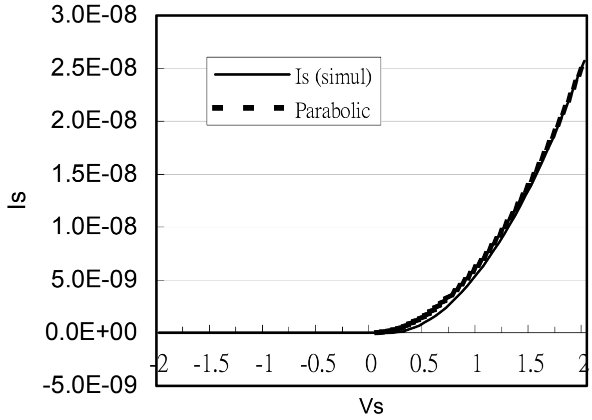

Fig. 3: Medici simulated substrate-subcollector junction current. Dashed line is a parabolic fitting curve.

3. Forward Current Transport Mechanism

The potential distribution in the substrate is calculated from Medici and plotted in Fig. 4. The substrate thickness is reduced to 25 μm for better convergence. It is observed that as the substrate bias Vs is varied from 0 to 2 V, the applied bias is sustained by the substrate only, not at the junction (denoted by distance 0). Therefore, the current is dominated by carrier transport in the intrinsic substrate region. This is very different from a pn junction, where the junction supports most external bias.

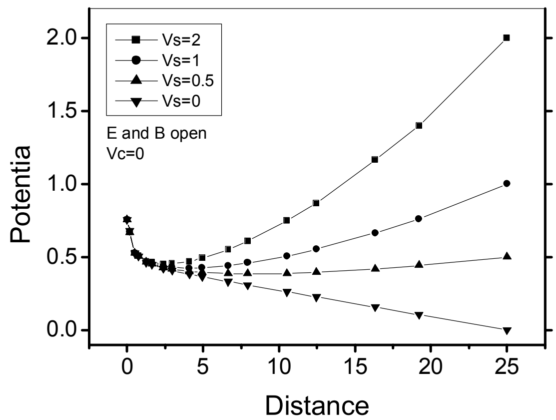

Fig. 4: Medici simulated potential distribution in the substrate of 25 μm thick. "Distance 0" denotes the substrate-subcollector junction.

Assuming carrier transport in substrate is collision limited. We can obtain the equation of current density [2]:

$$J = \frac{9\varepsilon\mu V_a^2}{8L^3} \qquad (2)$$

The current is proportional to the square of applied voltage, which has been observed in our measured and simulation results. It is also inversely proportional to the cube of substrate thickness L. Fig. 5 shows the simulated current at the junction for substrate thickness of 25 and 100 μm. The current of 25 μm is larger than that of 100 μm, and the ratio is also plotted in the same figure. As the forward bias Vs approaches 2 V, the ratio increases and approaches 64. This is consistent with the theoretical calculation from eq. (2), from which a 1:4 of substrate thickness yields a 64:1 of current.

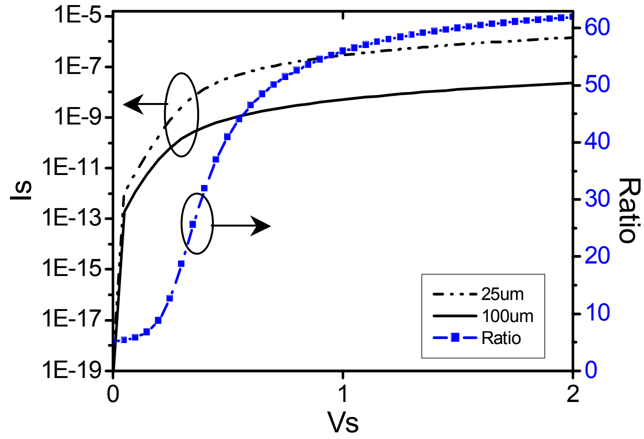

Fig. 5: Forward-biased substrate current simulated with Medici, for substrate thickness of 25 and 100 μm. The ratio of current is also plotted.

To account for the effect of substrate leakage on collector current (as shown in Fig. 1), we propose an equivalent circuit to modify the Gummel-Poon or VBIC model. Simulation result matches the measured data, as shown in Fig. 6.

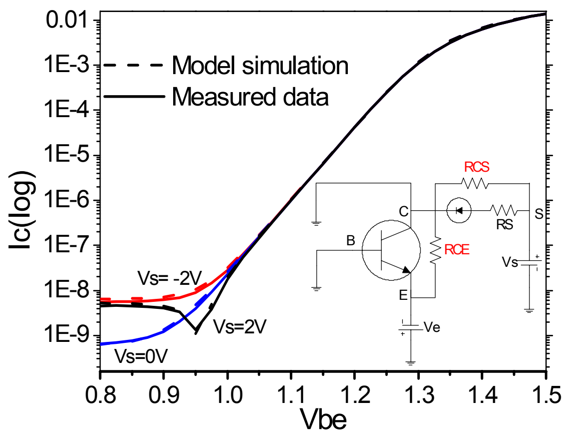

Fig. 6: Modified DC equivalent circuit (inset) and ADS simulation result. $V_C = V_B = 0$.

4. Conclusions

The current transport mechanism of the leakage current at substrate-subcollector junction has been identified. The forward current is much more significant when substrate thickness is reduced.

Acknowledgements

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