Chapter 3

Bias Dependences of Intrinsic Model Parameters

To design an optimal RF circuit, accurate device model is required. The accuracy of such model depends not only on how to establish its equivalent circuit with the correct understanding of the device physics but also on how to extract the element parameters appropriately. The intrinsic parameters of an HBT small-signal model are the most major factors determining the high-frequency performance of transistors. These parameters include intrinsic base-emitter capacitance, intrinsic base-collector capacitance, intrinsic base resistance, base-emitter dynamic resistance and transconductance. To realize the device behavior in detail, it is important to extract the model parameters with different bias conditions. Besides, we can develop a large-signal model based on the relations of model parameters and applied voltages.

In this chapter, we will discuss the intrinsic small-signal model parameters of SiGe HBTs with different bias conditions. S-parameters of devices were measured on wafer from 0.05GHz to 20GHz at 30 different bias points (base current I_b is from 1 μA to 10 μA and collector voltage V_{ce} is 0.2V, 0.25V, and 0.3V). The model parameters were obtained by using the parameter extraction method in Chapter 2.

3.1 Cutoff Frequency and Maximum Oscillation Frequency

The important figures-of-merit of an HBT, which are typically used to describe the high-frequency performance, are the cutoff frequency (f_T) and maximum oscillation frequency (f_{max}). The cutoff frequency and maximum oscillation frequency were determined as the frequency where the short-circuit current gain (h_{21}) was 0 dB and the frequency where the maximum stable gain/ maximum available gain (MSG/MAG) was 0 dB, respectively. The MSG/MAG and h_{21} were calculated from S parameters. Fig. 3-1 shows the f_T and f_{max} of a SiGe HBT as functions of collector current. The maximum values of cutoff frequency are about 26 GHz, 23GHz and 20GHz, respectively for different collector voltages. For an equivalent hybrid-π model of a bipolar transistor (as shown in Fig. 2-1), the cutoff frequency and maximum oscillation frequency can be simply expressed as

$$f_T = \frac{g_m}{2\pi C_\pi} \quad , \tag{3-1}$$

and

$$f_{\max} = \sqrt{\frac{f_T}{8\pi R_b C_{bc}}} \, , \tag{3-2}$$

where g_m is the intrinsic transconductance, C_π is the base-emitter capacitance, R_b is the base resistance, and C_{bc} is the base-collector capacitance. Since the f_T and f_{max} are mainly related to g_m, C_π, R_b, and C_{bc}, we are interested to know the bias dependences of these model parameters.

3.2 Intrinsic Transconductance and Excess Phase Delay

Figure 3-2(a) shows the intrinsic transconductance as a function of collector current. It can be seen that the transconductance increases linearly with the collector current in low current region. For low injection, the transconductance can be written as $g_m = I_C / V_T$, where

$V_T = kT/q$ is the thermal voltage. Therefore, g_m increases linearly with increasing collector current. When the collector current increases to higher values, the transconductance is no longer a linear function of collector current. In addition, it is clear that g_m is not equal at different collector voltages. It may be due to the self-heating effect and Kirk effect. When the transistor operates at high currents, the dissipation power will increase the junction temperature of device. As a result, the transconductance will be degraded.

Figure 3-2 (b) shows the excess phase delay (τ) as a function of collector current. The excess phase delay is related to the forward transit time and expressed as $\tau = \alpha_d \cdot \tau_F$ [21]. The forward transit time (τ_F) can be described by the following equation:

$$\tau_F = \frac{W_B{}^2}{\eta D_B} + (C_{bci} + C_{cs})R_c \tag{3-3}$$

The first term $W_B{}^2/\eta D_B$, called the base transit time (τ_B), represents the average time per carrier spent in diffusing across the neutral base region on width W_B. D_B is the diffusion coefficient of minority carriers in the base, and the parameter η is associated with the doping profile in the base. The second term is the delay associated with charging of the capacitances connected to the collector node (C_{bci} and C_{cs}) through R_c. Note that τ_F in fact also depends on I_c.

The excess phase delay increases with increasing collector current. It is due to the excess phase delay is direct relation with the base width. When the collector current increases, V*BE* also increases, and therefore V*CB* decreases. It causes the base-collector depletion width decrease and the base width increases hence the excess phase delay increases due to the distance of electron through base to collector also increases.

3.3 Intrinsic Base-Emitter Resistance and Capacitance

The bias dependence of base-emitter resistance (R_π) is illustrated in Fig. 3-3. R_π decreases with increasing base current through the following equation,

$$R_\pi = \frac{V_T}{n_b I_b} \quad . \qquad (3\text{-}4)$$

Where n_b is the ideality factor of base current. We can easily know that R_π is proportional inversely to the base current. It is related to the bias voltage across base and emitter junction.

Figure 3-4 shows the base-emitter capacitance (C_π) versus collector current. In low current region, C_π is almost proportional to I_c. The base-emitter capacitance can be expressed as $C_\pi = C_j + \tau q I_c / kT$, where C_j is the base-emitter junction depletion capacitance. In general, when the base-emitter junction is set at forward bias, the diffusion capacitance ($C_d = \tau q I_c / kT$)is extremely larger than depletion capacitance (C_j). The diffusion capacitance will be a predominant factor in the base-emitter capacitance. Fig. 3-4 also shows that C_π is relatively insensitive to V_{ce} in the low bias condition [22]. In high current condition, the C_π will rise rapidly with increasing collector current, as shown in Fig. 3-4. At high value of I_c, the base width will increase due to Kirk effect, making the increase of base charge and hence C_π.

3.4 Intrinsic Base-Collector Capacitance

Base-collector capacitance (C_{bc}) consists of extrinsic base-collector capacitance (C_{bcx}) and intrinsic base-collector capacitance (C_{bci}). C_{bcx} is bias independent. At low biases, C_{bci} is only depletion capacitance, because the base-collector junction is biased at reverse voltage. C_{bci} is proportional to the base-collector width inversely. The width of base-collector junction is dependent on the collector-base voltage (V_{cb}). Fig 3-5 shows that intrinsic base-collector capacitance as a function of collector current. The inverse dependence of C_{bci} on V_{ce} fits the simple pn-junction theory in that as V_{ce} increases, V_{cb} also increases, and therefore C_{bci} decreases. As the collector current increases to higher values, the dependence of C_{bci} on I_c becomes significant due to Kirk effect. In this bias condition, the base-collector junction will be forward biased, so the base-collector capacitance is dominant with diffusion capacitance.

3.5 Intrinsic Base Resistance

Base series Resistance (R_b) is consist of two parts. The first part is the resistance of the extrinsic base region (R_{bb}), which makes up the path between the base contact and the edge of the emitter region. The second part is the resistance of intrinsic base region (R_{bi}), which is located within the edges of the emitter. R_{bi} is also known as the base-spreading resistance. It is not well modeled by a single resistor, for two reasons. First, the resistance is actually distributed throughout the intrinsic base region. Second, because of the current crowding effect, the current density in the intrinsic base region is not uniform. Hence, the intrinsic base resistance is difficultly modeled by an explicit value. Current crowding can give beneficial effect of reducing R_{bi}. However, it can also give rise to localized heating at current levels that might be tolerable only if the current were uniformly distributed. Furthermore, the Kirk effect can occur at lower currents because of uneven current density across the active region of device [23].

Figure 3-6 shows the R_{bi} versus I_B, R_{bi} decreases with increasing I_B. It is due to the current crowding effect. The base is so narrow that the distributed resistance along it is quite high with I_B increasing, and the value of the ohmic drop can cause the base-emitter voltage drop to very high potential between the E-B junction. The voltage drop sets up an strong electric field from base to edge of emitter, and it results in the electrons heap at the emitter edge. It causes the equivalent distance contraction between base and emitter, and the intrinsic base resistance reducing.