ΔI_{Sub} Method for BJT Collector Series Resistance Determination

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A new ΔI_{Sub} method for determining BJT collector series resistance is presented. This method is based on the use of the substrate current caused by the parasitic pnp transistor if the npn transistor is in a state of saturation.

Methods for determining the BJT parasitic series resistances can be divided into AC and DC. A well-known AC method for R_B determination is the input impedance cycle diagram method proposed by Sansen and Meyer [1]. Other AC methods are presented by Neugroschel [2] and De Graaf [3]. The DC method includes a large number suitable for RE and RC determination, for example, the methods by Kulke - Miller [4], Logan [5], Getreu [6], Incecik [7], Mack and Horowitz [8], Ning and Tang [9], Park et.al. [10] and Verzellesi et.al. [11]. A detailed discussion of these methods is beyond the scope of this article; for a survey see [12].

This article describes a new DC method (the ΔI_{Sub} method) for determining the parasitic collector series resistance of integrated bipolar transistors.

The ΔI_{Sub} method was developed [13] based on the observation that the substrate current, caused by the parasitic pnp transistor if the npn transistor is in saturation or in quasi-saturation, shows a distinct increase with increasing voltage drop across the collector resistance. We can observe a linear range in the substrate current characteristic where the current is ideal. This range is useful for determination of the collector resistance.

Figure 1 shows the cross section of the transistor, together with the measurement circuit, used for this method. This circuit is appropriate to the circuit usually used for measurements of the forward active transfer characteristics, except the negative collector potential. That is why the npn transistor is for low base-emitter voltages in weak saturation. With increasing base emitter voltage the collector current, the voltage drop across R_C and the substrate current increases, and the transistor will attain hard saturation.

As an example, the transfer characteristics of the npn transistor NN03 in Figure 2 shows: the substrate current is nearly constant with 5 E-11 A if the base-emitter voltage of the pnp transistor is lower than 0.7V. This current is the transfer current of the pnp transistor. With increasing npn base-emitter voltage we can observe a transition range, a linear range and then a high current range for the substrate current characteristic. In the linear range the substrate current is ideal. In that range it is now possible to determine the unknown base-emitter voltage of the pnp transistor

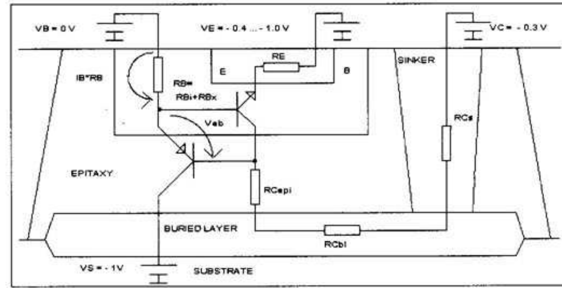

Figure 1. Cross Section of npn and Parasitic pnp Transistor

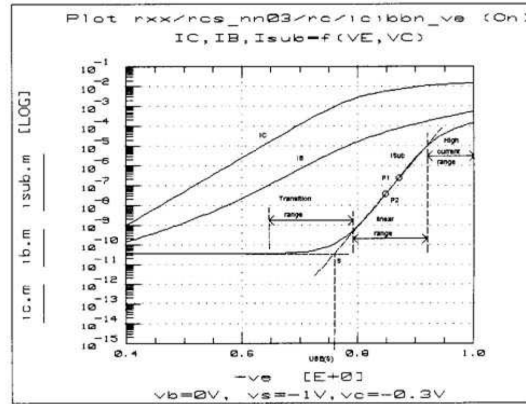

Figure 2. Transfer Characteristics I_C, I_B, I_{Sub} = f(V_{BE}), DUT: NN03, V_{Sub} = -1V, V_C = -0.3V

using the ratio of two substrate current values (P1 and P2 in Figure 2). From Figure 1 it is clear that the base-emitter voltage of the pnp transistor is given as:

$$v_{eb(pnp)} = V_B - I_B R_B + I_C R_C - V_C \quad (8)$$

Rearranging equation (1) for two operating points P1 and P2 in the linear substrate current range, we have:

$$v_{eb(pnp)1} - V_{eb(pnp)2} = [I_{CI} - I_{C2}]R_C - [I_{B1} - I_{B2}]R_B \quad (9)$$

The difference of the base-emitter voltages can be calculated now from the ratio of the two substrate current values I_{Sub1} and I_{Sub2}. (Note that, contrary to Park's downward method, only one substrate current characteristic is used for the ΔI_{Sub} method.)

$$\frac{I_{SUB1}}{I_{SUB2}} = \exp\frac{V_{be(pnp)1} - V_{be(pnp)2}}{V_T} \quad (10)$$

Combining equations 2 and 3 gives for the collector resistance:

$$R_C = \frac{V_T \ln\frac{I_{Sub1}}{I_{Sub2}} + [I_{B1} - I_{B2}]R_B}{I_{C1} - I_{C2}} \quad (11)$$

Assuming a negligible variation of the base resistance voltage drop for the two operating points, this expression reduces to:

$$R_C = \frac{V_T \ln \frac{I_{Sub1}}{I_{Sub2}}}{I_{C1} - I_{C2}} \qquad (12)$$

Measurements

To evaluate the ΔI_{Sub} method we used the npn transistor NN03 as the DUT. This device is made with an 18V standard bipolar process and is part of the SMI design library. The emitter size is 14 µm × 16 µm. The measurement of the transfer characteristic was made at a collector voltage of U_C = -0.3V (Figure 3). R_C was calculated according to equation (5) using the linear range of the substrate current characteristic (extraction bounds U_E = 760 ... 900 mV). The result is a characteristic with a clear maximum; Figure 4 shows R_C values between 32.3 and 34.3 Ohm. Because the main assumption for this method, made by equation (3), is only given in the truly linear range of the substrate current characteristic, we can conclude that the maximum value of $R_C = f(I_C)$ is the true R_C value. This value depends only slightly on the used substrate potential (Table 1).

A comparison to other results for the NN03 extracted using the methods by Logan and Park shows a good agreement with Park's downward method and Logan's forced beta method for B_{FB} = 20. Additional measurements were made for a fast 12V npn and a 50V npn device (see Table 2). As we can see, the agreement to the forced beta results depends on the used B_{FB} value. And, the ΔI_{Sub} method was also found to be convenient for a lateral pnp device (in a modified manner) [14].

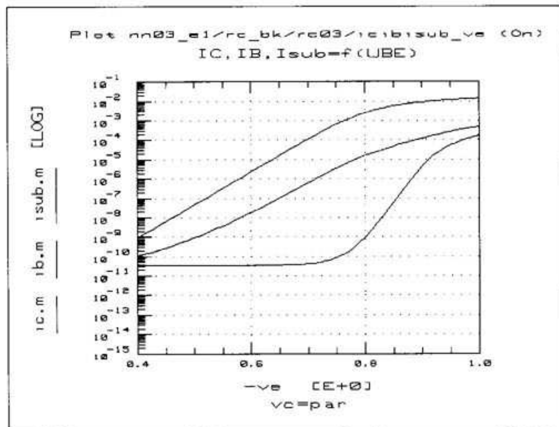

Figure 3. Transfer curves I_C, I_B, $B_N = f(V_{BE})$, V_C = -0.3V, V_{Sub} = -1V

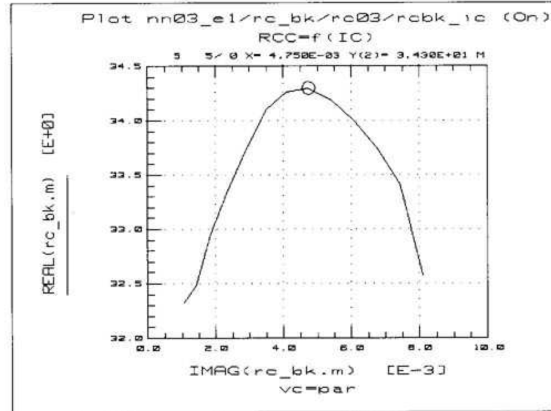

Figure 4. $R_C = f(I_C)$ According to Equation 5; Extraction Bounds U_E = 760 ... 900 mV

Table 1. Extracted R_C Values According to ΔI_{Sub} Method

V_{Sub}	-0.2V	-0.3V	-0.4V
Extraction bounds V_E / mV	800 ... 950	760 ... 900	700 ... 900
R_C / Ohm	33.8	34.3	34.0

Table 2. Comparison of Extracted R_C values (Ohm)

Method	Park (Downward Method)	Logan (B_{FB} = 20)	ΔI_{Sub} (V_{Sub}) = -0.3V
NN03 (V_{CE0} = 18V)	33.8	33.8	34.3
NN11 (V_{CE0} = 12V)	46.9	73.3	42.8
NN01 (V_{CE0} = 50V)	150	112	161

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