An Improved Parameter Extraction Method of SiGe HBTs' Substrate Network

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***Abstract*—In this letter, an improved method for substrate network parameter extraction of SiGe heterojunction bipolar transistors (HBTs) is proposed. It is found that, without taking the intrinsic circuit elements into consideration, the conductance of substrate network will be underestimated while the susceptance of substrate network will be overestimated. Therefore, an iteration procedure is developed to determine the intrinsic circuit elements of SiGe HBTs first. The intrinsic circuit elements are then applied to remove their influence on the substrate network parameter extraction. Compared with the conventional method, the proposed one can avoid some unphysical modeling results and provide reliable substrate network parameters.**

***Index Terms*—SiGe HBTs, substrate network parameter extraction.**

I. INTRODUCTION

SiGe heterojunction bipolar transistors (HBTs) are the first practical bandgap-engineered silicon devices. Due to the higher performance than Si devices and higher integration level than III-V devices, SiGe HBTs are suited ideally for large-volume manufacturing of radio frequency (RF) transceiver systems [1], [2]. An accurate extraction method for small-signal equivalent circuit of SiGe HBTs is vital for designing a circuit and optimizing device performance. For the extraction of small-signal SiGe HBTs equivalent circuits from S-parameters, extrinsic inductances, resistances and substrate network are initially determined and subsequently the rest of parameters are extracted from analytical formulations [3], [4]. Recently, several methods have been investigated to extract the substrate network parameters from the frequency response of $(Y_{22}+Y_{21})$ [5] or using extra test structures [6]. However, we found that the interaction of intrinsic circuit elements makes $(Y_{22}+Y_{21})$ deviate from the admittance of substrate network and the modeling results are not so successful if the parameter extraction of substrate network is directly performed on the measured $(Y_{22}+Y_{21})$. Therefore, to extract the substrate network parameters, the intrinsic circuit elements of SiGe HBTs should be determined first. By expanding the essence of the technique in [7], we present an improved method for SiGe HBTs substrate network parameter extraction. The proposed extraction procedure was experimentally verified on several SiGe HBTs fabricated with a commercial 0.35-μm BiCMOS technology [8].

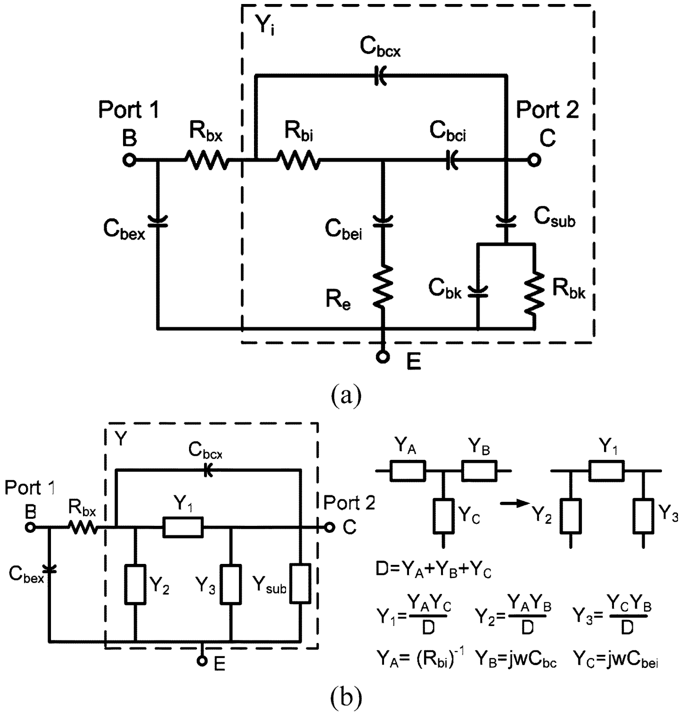

Fig. 1. (a) Simplified small-signal equivalent circuit model for a SiGe HBT biased in the cutoff mode operation after pad de-embedding and removing the extrinsic inductances and collector resistance. (b) Application of the $T \leftrightarrow \Pi$ transformations to the HBT device equivalent circuit shown in (a).

II. THEORETICAL ANALYSIS

Fig. 1(a) shows the small-signal equivalent circuit of a SiGe HBT under cutoff mode operation after removing some extrinsic elements. An OPEN pad de-embedding is performed to remove the pad parasitic. The extrinsic resistances ($R_{\rm bx}$, $R_{\rm e}$ and collector resistance) and inductances are determined by biasing the SiGe HBTs in saturation region and driving a large forward base current [3], [9]. After removing the extrinsic inductances and collector resistance, the equivalent circuit is divided into two parts, the inner part $(Y_{\rm i})$ containing the bias-dependent elements, and the outer part with the mostly bias-independent extrinsic elements. The $C_{\rm bex}$ represents the remaining base-emitter parasitic capacitance not removed. The substrate network $(Y_{\rm sub})$ is constituted of substrate-collector depletion capacitance $C_{\rm sub}$, substrate resistance $R_{\rm bk}$ and bulk capacitance $C_{\rm bk}$ accounting for Si dielectric behavior.

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For simplicity, the influence of emitter resistance (R_{e}) has been neglected where the approximation is valid for $(\omega R_{\mathrm{e}} C_{\mathrm{bei}})^2 \ll 1$. We transform the intrinsic part of the device equivalent circuit (R_{bi}, C_{bei}, C_{bci}) using the well-known $T \leftrightarrow \Pi$ transformations shown in detail on the right side of Fig. 1(b). If temporarily neglecting the influence of extrinsic base resistance (R_{bx}), and observing Y_{i} in Fig. 1(b), we can derive

$$Y_{22,i} + Y_{21,i} = Y_{\mathrm{sub}} + Y_3 \tag{1}$$

where

$$\begin{aligned} Y_{\mathrm{sub}} = {} & \frac{\omega^2 R_{bk} C_{\mathrm{sub}}^2}{1 + \omega^2 R_{bk}^2 (C_{bk} + C_{\mathrm{sub}})^2} \\ & + j\omega C_{\mathrm{sub}} \left(\frac{1 + \omega^2 R_{bk}^2 C_{bk} (C_{bk} + C_{\mathrm{sub}})}{1 + \omega^2 R_{bk}^2 (C_{bk} + C_{\mathrm{sub}})^2} \right) \end{aligned} \tag{2}$$

$$\begin{aligned} Y_3 = {} & \frac{-\omega^2 C_{bci} C_{bei} R_{bi}}{1 + \omega^2 R_{bi}^2 (C_{bci} + C_{bei})^2} \\ & + j \frac{\omega^3 C_{bci} C_{bei} (C_{bci} + C_{bei}) R_{bi}^2}{1 + \omega^2 R_{bi}^2 (C_{bci} + C_{bei})^2}. \end{aligned} \tag{3}$$

From (1), it is clear that $(Y_{22,\mathrm{i}} + Y_{21,\mathrm{i}})$ deviates from Y_{sub} by an additional term, Y_3, which is constituted of the intrinsic circuit elements. If the extraction of substrate network parameters is performed on $Y_{22,\mathrm{i}} + Y_{21,\mathrm{i}}$, the conductance of substrate network will be underestimated and the susceptance of substrate network will be overestimated.

III. EXTRACTION OF INTRINSIC CIRCUIT ELEMENTS

To extract substrate network parameters, Y_3 should be determined first. The proposed iteration procedure to determine Y_3 is listed as follows.

1) Under the operation condition of $V_{\mathrm{CE}} = 0$, reverse and/or low forward V_{BE}, C_{bex} is estimated from the following well-known equation

$$\begin{aligned} C_{bex} + C_{bei} & = \frac{1}{\omega} \mathrm{Im}(Y_{11} + Y_{12})|_{\text{low frequency}} \\ & = C_{bex} + C_{be0} (1 - V_{be}/V_{bi})^{-m_{be}}. \end{aligned} \tag{4}$$

The estimation of C_{bex} is carried out by fitting $(C_{\mathrm{bex}} + C_{\mathrm{bei}})$ to the expression $(1 - V_{be}/V_{bi})^{-m_{be}}$. It is important to mention that the obtained value of C_{bex} only serves as an initial value and it will be corrected in the following steps.

2) Y_{i} is obtained by removing C_{bex} and R_{bx} from the total Y parameters.

3) As described in [7], a linear relation can be obtained as

$$\frac{\omega^2}{\mathrm{Re}(Y_{11,i})} = \frac{1}{R_{bi} (C_{bei} + C_{bci})^2} + R_{bi} \omega^2. \tag{5}$$

By plotting $\omega^2 / \mathrm{Re}(Y_{11,\mathrm{i}})$ versus ω^2, $C_{\mathrm{bei}} + C_{\mathrm{bci}}$ can be determined from $(R_{\mathrm{bi}} \times \beta)^{-0.5}$ where R_{bi} and β are the slope and Y-axis intercept, respectively.

4) Another useful relation is derived to separate C_{bei} from $C_{\mathrm{bei}} + C_{\mathrm{bci}}$ and is shown as

$$C_{bei} = \frac{\mathrm{Re}(Y_{11,\mathrm{i}} + Y_{12,\mathrm{i}})}{\mathrm{Re}(Y_{11,\mathrm{i}})} (C_{bci} + C_{bei}). \tag{6}$$

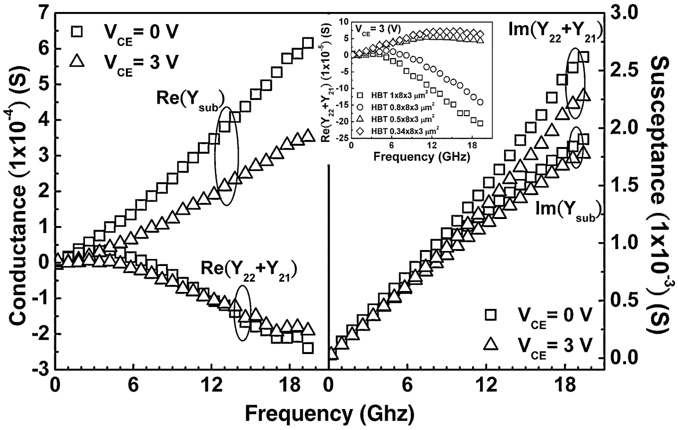

Fig. 2. Measured $(Y_{22} + Y_{21})$ and calculated Y_{sub} by removing Y_3 from $(Y_{22,\mathrm{i}} + Y_{21,\mathrm{i}})$ (a) $\mathrm{Re}(Y_{22} + Y_{21})$ and $\mathrm{Re}(Y_{\mathrm{sub}})$ and (b) $\mathrm{Im}(Y_{22} + Y_{21})$ and $\mathrm{Im}(Y_{\mathrm{sub}})$. Insert gives measured $(Y_{22} + Y_{21})$ with different emitter dimensions at $V_{\mathrm{CE}} = 3$ V.

5) The new C_{bex} is then derived from

$$C_{bex} = \frac{1}{\omega} \mathrm{Im}(Y_{11} + Y_{12})|_{\text{low frequency}} - C_{bei} \tag{7}$$

and sent back to step 2) to repeat the calculation to step 5). Once a stable C_{bex} is obtained, the circuit elements, R_{bi}, C_{bei}, and C_{bci}, are extracted. Substituting extracted R_{bi}, C_{bei}, and C_{bci} back to (3), Y_3 is obtained. From (1), Y_{sub} is then obtained by removing Y_3 from $Y_{22,\mathrm{i}} + Y_{21,\mathrm{i}}$.

IV. RESULTS AND DISCUSSION

To amplify the influence of intrinsic circuit elements on the substrate network extraction, we apply the proposed method on a large area SiGe HBT. Fig. 2 shows the measured $(Y_{22} + Y_{21})$ and Y_{sub} for a $1 \times 8 \times 3\ \mu\mathrm{m}^2$ SiGe HBT at $V_{\mathrm{BE}} = 0$ and $V_{\mathrm{CE}} = 0$, 3 V. Due to the interaction of intrinsic circuit elements, $\mathrm{Re}(Y_{22} + Y_{21})$ becomes negative and $\mathrm{Im}(Y_{22} + Y_{21})$ shows a deviation from $\mathrm{Im}(Y_{\mathrm{sub}})$ at operation frequency beyond 5 and 10 GHz, respectively. As shown in the inset of Fig. 2, the negative value of $\mathrm{Re}(Y_{22} + Y_{21})$ can still be found in other SiGe HBTs with emitter width larger than 0.5 μm. From (3), we found the negative value of $\mathrm{Re}(Y_{22} + Y_{21})$ comes from the negative part of $\mathrm{Re}(Y_3)$. Since the Y_3 is constituted of R_{bi}, C_{bei}, and C_{bci}, the negative value of $\mathrm{Re}(Y_{22} + Y_{21})$ is more likely to be appeared in the SiGe HBTs with larger emitter area. If the extraction is directly performed on $Y_{22} + Y_{21}$, an unphysical negative substrate resistance will be obtained.

To extract the substrate network parameters, two linear equations are derived from Y_{sub} and are shown as [6]

$$\begin{aligned} \frac{\mathrm{Im}(Y_{\mathrm{sub}})}{\omega \mathrm{Re}(Y_{\mathrm{sub}})} & = \frac{1}{\omega^2 R_{bk} C_{\mathrm{sub}}} + R_{bk} \frac{C_{bk} (C_{bk} + C_{\mathrm{sub}})}{C_{\mathrm{sub}}} \\ & = \frac{1}{\omega^2} k_1 + k_2 \end{aligned} \tag{8}$$

$$\begin{aligned} \frac{1}{\mathrm{Re}(Y_{\mathrm{sub}})} & = \frac{1}{\omega^2 R_{bk} C_{\mathrm{sub}}^2} + R_{bk} \left(\frac{C_{bk} + C_{\mathrm{sub}}}{C_{\mathrm{sub}}} \right)^2 \\ & = \frac{1}{\omega^2} m_1 + m_2. \end{aligned} \tag{9}$$

As indicated in Fig. 3, k_1 and m_1 can be obtained from the linear regression of (8) and (9). Then C_{sub} and R_{bk} are calculated as

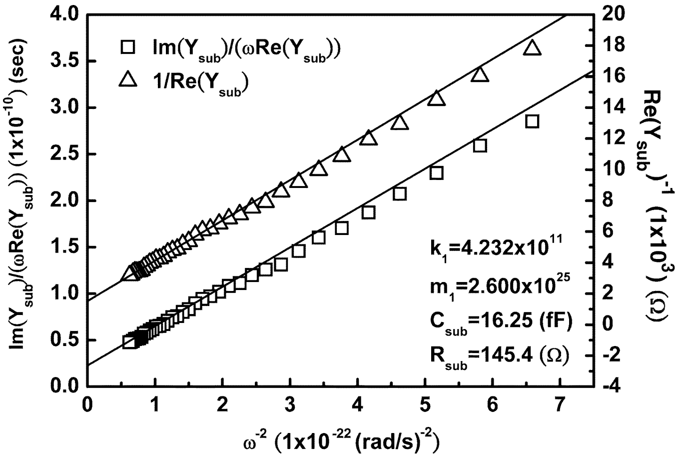

Fig. 3. Extracting the substrate network parameters by plotting $\mathrm{Im}(Y_{\mathrm{sub}})/(\omega \mathrm{Re}(Y_{\mathrm{sub}}))$ and $1/\mathrm{Re}(Y_{\mathrm{sub}})$ versus $1/\omega^2$. The SiGe HBT is biased at $V_{\mathrm{CE}} = 3$ V and $V_{\mathrm{BE}} = 0$ V.

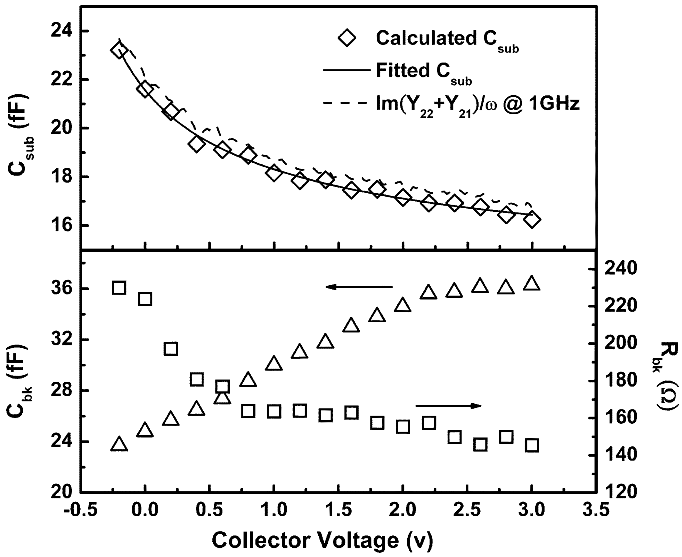

Fig. 4. Extracted substrate-collector depletion capacitance C_{sub}, substrate resistance R_{bk} and bulk capacitance C_{bk} as a function of applied collector voltage. In the upper figure, the solid line is the empirical fitting for C_{sub} and the dashed line is the measured $\mathrm{Im}(Y_{22} + Y_{21})/\omega$ at low frequency (1 GHz).

k_1/m_1 and $m_1/(\mathrm{k}_1)^2$, respectively. Having determined C_{sub} and R_{bk}, C_{bk} is calculated as $C_{bk} = (C_{\mathrm{sub}}^2/(R_{bk}\mathrm{Re}(Y_{\mathrm{sub}})) - (\omega R_{bk})^{-2})^{0.5} - C_{\mathrm{sub}}$ [4].

Fig. 4 shows the collector voltage dependence of the extracted substrate network parameters. The extracted C_{sub} is close to the capacitance value extracted from $\mathrm{Im}(Y_{22} + Y_{21})/\omega$ measured at low frequency. The solid line shown in Fig. 4 is the empirical fitting for C_{sub} by the equation, $C_{\mathrm{sub}} = C_{sub,p} + C_{sub,0}(1 - V_{ce}/V_{sci})^{-m_{sc}}$, and the fitting values are 12.03 fF, 9.52 fF, 0.658 V, and 0.45 for $C_{\mathrm{sub,p}}$, $C_{\mathrm{sub,0}}$, V_{sci}, and $\mathrm{m_{sc}}$, respectively. The increased C_{bk} and decreased R_{bk} probably indicate the reduction of Si bulk region due to the increase of the collector-substrate depletion width [10].

V. CONCLUSION

In this letter, an improved technique for SiGe HBTs' substrate network parameter extraction is proposed. To erase the influence of intrinsic circuit elements on the substrate network parameter extraction, an iteration procedure is developed to determine intrinsic circuit elements before the extraction of substrate network parameters. Two linear equations are derived from Y_{sub} and are used to extract substrate network parameters. Compared with the previous method, the proposed one requires no extra test structures, avoids some unphysical modeling results and provides reliable substrate network parameters.

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