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# Parameter Extraction and Optimization for New Industry Standard VBIC Model

Invited paper

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*A new bipolar transistor model called VBIC has recently been developed and is likely to replace the Gummel-Poon model as the new industry standard bipolar transistor model. This paper seeks to develop an accurate, comprehensive and efficient methodology to extract the parameters for the VBIC model. Results obtained from measurement, Gummel-Poon model, and VBIC using the parameters extracted will be compared under various bias and operation conditions.*

## 1. Introduction

The bipolar junction transistor (BJT) is one of the most widely used semiconductor devices in manufacturing integrated circuits and electronic components. Because of its superior speed performance, such a device has found wide applications in high-speed switching and digital electronics systems. To carry out accurate simulation of integrated circuits involving bipolar transistors, it is imperative to have an accurate model for the bipolar transistor, as well as an efficient software which can be used to extract the parameters associated with the bipolar transistor model.

The SPICE Gummel-Poon (SGP) model [1] has been the industry standard bipolar transistor model for more than 20 years. Users of the SGP model, however, have found it to be inadequate in representing many of the physical effects important in modern bipolar transistors. Recently, a group of representatives from the integrated circuit and computer-aided design industries have collaborated and developed a new industry standard bipolar model called the vertical bipolar inter-company model (VBIC) [2]. While the existing parameter extraction techniques for the SGP model are still applicable for some VBIC parameters, using the advanced features of VBIC requires the development of new parameter extraction and optimization procedures.

This paper seeks to develop an accurate, comprehensive and efficient methodology to extract the parameters for the VBIC model. First, the SGP and VBIC models will be reviewed, and the framework and advanced features of VBIC model discussed. This will be followed by the development of the VBIC parameter extractions method. A numerical procedure for optimizing the extracted parameters will also be recommended. Finally, results calculated from the VBIC model using the parameters extracted from the present method, calculated from the SGP model, and obtained from measurements will be compared. It should be pointed out that, due to the large number of VBIC parameters, the parameters extracted and optimized in this paper are those associated with dc and room temperature operations. Extraction of parameters associated with ac, low temperature, and high temperature will be reported elsewhere in the future.

## 2. Review of VBIC Model

The equivalent circuit of VBIC model is shown in Fig. 1. Unlike the SGP model, which has three terminals, the VBIC is a four-terminal model comprising the base, emitter, collector, and substrate denoted by the letters b, e, c, and s, respectively, and the currents flowing into these terminals are $I_b$, $I_e$, $I_c$, and $I_s$. The other nodes in the VBIC are the extrinsic base bx, parasitic base bp, intrinsic base bi, intrinsic emitter ei, intrinsic collector ci, and extrinsic collector cx. The VBIC model includes the following features that make it distinct from the SGP model. First, the effect of parasitic substrate PNP transistor is included by a simplified SGP model (represented in Fig. 1 by the SGP equivalent circuit connected to the substrate terminal with components denoted by a subscript p). Second, the quasi-saturation behavior is modeled with the elements $R_{CI}$, $Q_{bcx}$, and a modified $Q_{bc}$ [3]. Third, the effect of excess phase is modeled with a second-order network (see Fig. 1) that implements the Weil-McNamee approximation [4]. Fourth, in addition to the conventional strong avalanche current, a weak avalanche current $I_{gc}$ is added for the base-collector junction. Fifth, to account for the extrinsic capacitances associated with the regions in which the $p^+$ base and $n^+$ emitter are overlapped, two constant capacitances $C_{BE0}$ and $C_{BC0}$ are included in the VBIC model. Finally, a self-heating model (see Fig. 1) is included as a separate option for the VBIC. The model consists of the thermal resistance $R_{TH}$ and capacitance $C_{TH}$, along with the thermal power source $I_{th}$, which couples the power generated in the bipolar transistor to the thermal network. The local temperature rise at node t in the thermal network is linked to the electrical model through the temperature mappings of the model parameters.

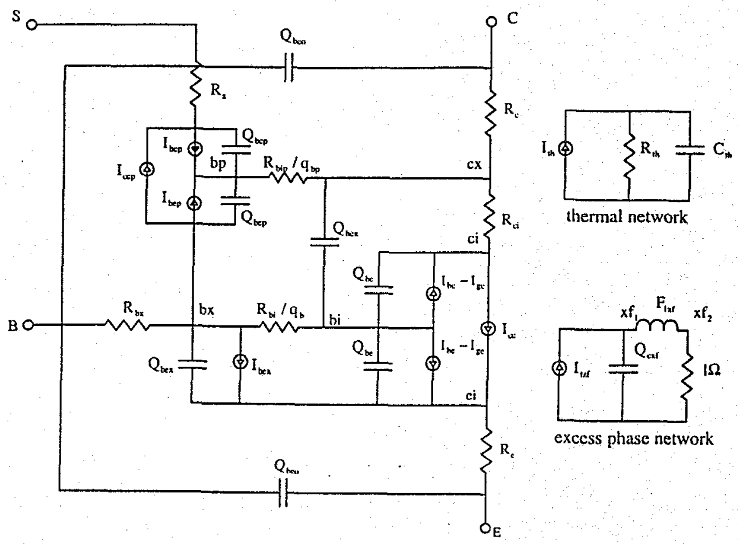


Fig. 1 Equivalent circuit for the new industry standard VBIC bipolar transistor model. The model includes two options, thermal network and excess phase network, to account for the effects of self-heating and excess phase in modern bipolar devices.

### 3. VBIC Parameter Extraction and Optimization

The VBIC parameter extraction and optimization method developed in this paper is coded in S+ statistical language and is based on the experimental data measured from bipolar transistors fabricated at Lucent Technologies, Orlando, Florida. The schematic of the device cross section is given in Fig. 2. Because the VBIC model has a very large number of parameters (i.e, more than 80 parameters), we will limit in the paper to the extraction and optimization of parameters associated with the dc operation at room temperature (i.e., about 50 parameters), and parameter extraction associated with ac, low temperature, and high temperature operations will be a subject of our future research.

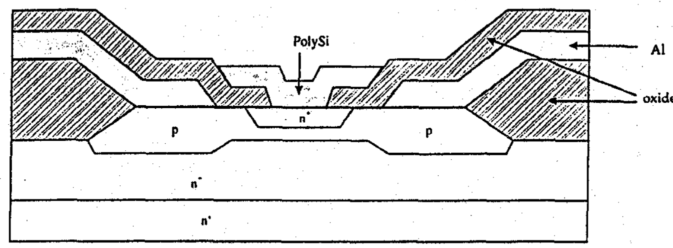


Fig. 2 Schematic of the bipolar transistor fabricated at Lucent Technologies and used in the present VBIC parameter extraction.

Our extraction and optimization procedure follows in general the approach of Seitchik et al. [4] and uses the constrained nonlinear least square method. The extraction procedure is fully automated and is carried out using a software coded in S+ statistical language. The optimization of a particular extraction function E is given by

$$E[P^{(k+1)}] = E[P^k] - [J^T \cdot J]^{-1} \cdot J^T \cdot W[R(P^k)] \tag{1}$$

where P is the vector of model parameter, k denotes the kth iteration step, J is the Jacobian matrix, T presents the transpose of the matrix, W is the weight function, and R is the residue between the measurement data and kth model playback.

Fig. 3 shows the flowchart of the extraction and optimization procedure we have developed. First, the parameters to be extracted are selected, and initial guesses (the default values are normally used) are given. Then the model calculations based on these parameters values are compared with measurements, which provides the information regarding the region to be fitted as well as whether the residue of the two meets the specified error requirement. The process is repeated until the residue is within the error specification. This is followed by the extraction of next group parameters, and the procedure is completed when all parameters are determined.

The order of parameter extraction and optimization is important, as a non-optimal sequence will result in less accurate parameters being extracted. The steps for extracting and optimizing the VBIC parameters are given in sequence below.

### *3.1 Junction parameters*

The parameters associated with the emitter-base and base-collector space-charge regions are first extracted. From $C_{be}$ versus $V_{be}$ data, in reverse bias and low forward bias regions, extract $C_{JE}$, $P_E$, and $M_E$. From $C_{bc}$ versus $V_{bc}$ data, in reverse bias and low forward bias regions, extract $C_{JC}$, $C_{JEP}$, $P_C$, and $M_C$. From $C_{sc}$ versus $V_{sc}$ data, in reverse bias and low forward bias regions, extract $C_{JCP}$, $P_S$, and $M_S$. Optimize the above parameters.

### *3.2 Early effect parameters*

The next step is to extract the parameters associated with the Early effect. The junction parameters extracted in the previous section can be used to calculate the forward and reverse Early voltages.

### *3.3 Low-voltage parameters*

The linear region (i.e., low-voltage region) in the Gummel plot, which is not influenced by the series resistances and high-voltage effects, provides useful information for extracting the model parameters associated with the current transport in bipolar transistors. The approach of extracting low-voltage parameters is the same as that used in the SGP model parameter extraction. However, since the VBIC model incorporates several improved features, more parameters need to be determined, and the extraction procedure is more complicated.

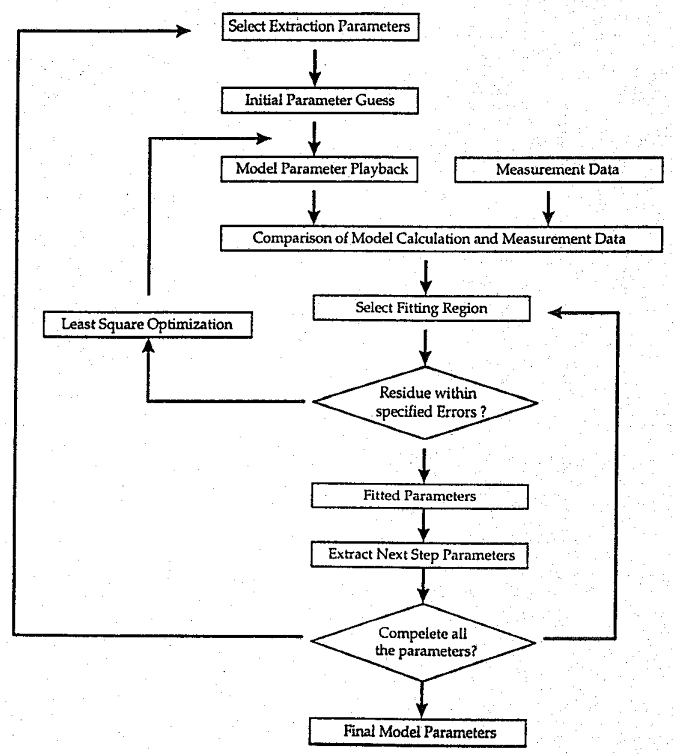


Fig. 3 Flowchart for extraction and optimization of VBIC parameters.

From the forward Gummel plot, extract the following parameters: $I_s$, $N_F$, $I_{BEI}$, $N_{EI}$, $I_{BEN}$, and $N_{EN}$. From the reverse Gummel plot, extract the following parameters: $I_s$, $N_R$, $I_{BCI}$, $N_{CI}$, $I_{BCN}$, $N_{CN}$, $I_{SP}$, $W_{SP}$, $N_{SF}$, $I_{BEIP}$, and $I_{BENP}$. Note that the parameters extracted include the parasitic PNP transistor current components. This is because, in the reverse Gummel plot, the base-collector junction is forward biased, and the parasitic transistor is conducting. Optimize these parameters. The voltage range of this extraction is normally between 0.4 and 0.8 V. It should be emphasized that this set of parameters is relatively easy to extract and requires minimal optimization due to the fact that they are isolated from the effects associated with the high current region.

Figs. 4(a) and (b) show the comparisons of the modeled and measured forward and reverse Gummel plots, respectively. The agreement between the model and measurements is excellent in the linear region. Beyond this region, however, the model fitting is far from acceptable. This results from the fact that only the parameters associated with the low-voltage characteristics were used in model calculations.

### *3.4 Knee current parameters*

The knee currents are the currents at which the I-V data starts to deviate from its linear relationship. These parameters ($I_{KF}$ and $I_{KR}$) can be estimated from the forward beta (i.e., forward current gain) versus $I_c$ and reverse beta (i.e., reverse current gain) versus $I_e$ plots by taking the current where the beta value is dropped to half of its peak value. Since $I_{KF}$ and $I_{KR}$ are influenced by the high-voltage effects, their values need to be optimized later when other parameters are extracted.

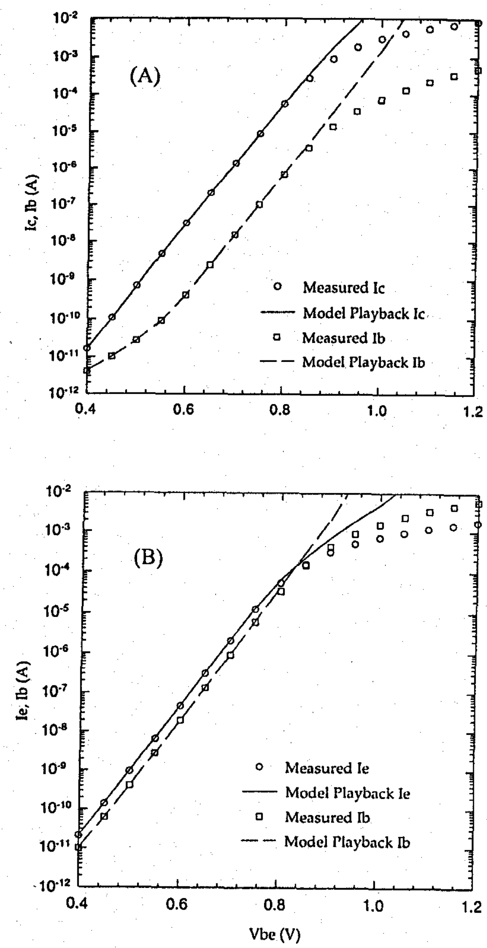


Fig. 4 (a) Forward and (b) reverse Gummel plots obtained from measurements and from VBIC model using the parameters extracted from the low-voltage region.

### *3.5 High-voltage parameters*

High-voltage effects in bipolar transistor make the parameter extraction difficult. They include voltage drops on series resistances, parasitic currents and resistances, high-level injection, quasi-saturation, and avalanche breakdown. Since these effects are interacting with each other, one subset of parameters cannot be extracted independently from the others. A better way to do this is to extract and optimize a subset of parameters using other subsets of parameters which are not yet optimized. This process is then repeated until all the parameters associated with the high-voltage region are optimized.

#### *(a) Forward Gummel plot*

In the forward Gummel plot at high voltages, extract the series resistances $R_{BX}$, $R_{BI}$, and $R_E$. Next, these series resistances, together with the knee currents extracted previously, are optimized.

#### *(b) Quasi-saturation and saturation*

The parameters associated with the quasi-saturation effect can be extracted from the forward current-voltage (forward I-V) characteristics under quasi-saturation and saturation operations. They include the series resistances $R_{CX}$ and $R_{CI}$, and quasi-saturation parameters $V_O$, $G_{AMM}$, and $H_{RCF}$. In addition, since the base-collector junction is forward biased and the parasitic PNP transistor is conducting, the parasitic current components extracted previously, together with the parameters extracted here, need to be optimized.

### *(c) Reverse Gummel plot*

In the reverse Gummel plot at high voltages, extract the parasitic resistance $R_{BP}$ and $R_S$, and optimize all the former parameters.

### *(d) Weak avalanche breakdown*

Next, based on the I-V characteristics in avalanche breakdown region, we carry out the extraction and optimization of the parameters $A_{VC1}$ and $A_{VC2}$ associated with forward weak avalanche breakdown and parameters $A_{VE1}$ and $A_{VE2}$ associated with the reverse weak avalanche breakdown.

### *3.6 Global parameter optimization*

Finally, all the above dc parameters are optimized to obtained the best fitting for the current gain and output conductance. Figs 5(a)-(b) and 6(a)-(b) illustrate the forward and reverse current gains and forward and reverse output conductances, respectively, obtained from the VBIC model playback and measurements. The predictions from the VBIC model using the parameters extracted compare favorably with measurements.

## 4. Comparison with the Gummel-Poon Model

To illustrate the advantage of the VBIC model over its Gummel-Poon counterpart, we compare the dc characteristics of another bipolar transistor obtained from VBIC model, SGP model, and measurements. Figs. 7(a)-(c) and 8(a)-(c) show the forward and reverse characteristics of the BJT, respectively, calculated from the SGP model with the SGP parameters extracted from the conventional method, calculated from the VBIC model with the VBIC parameters extracted from the present method, and obtained from measurements. The results indicate that the SGP model is less accurate when the BJT is operating at relatively high

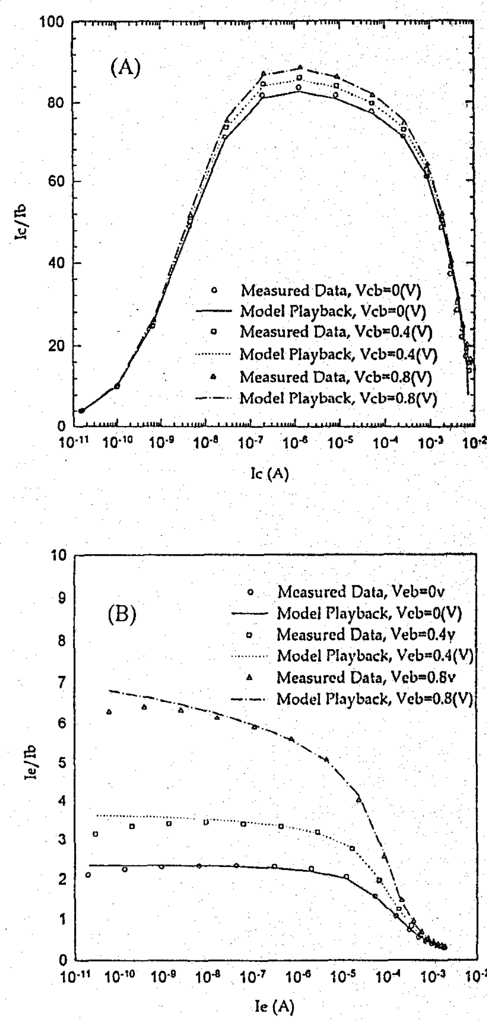


Fig. 5 (a) Forward and (b) reverse current gain versus current obtained from measurements and from VBIC model using all the parameters extracted.

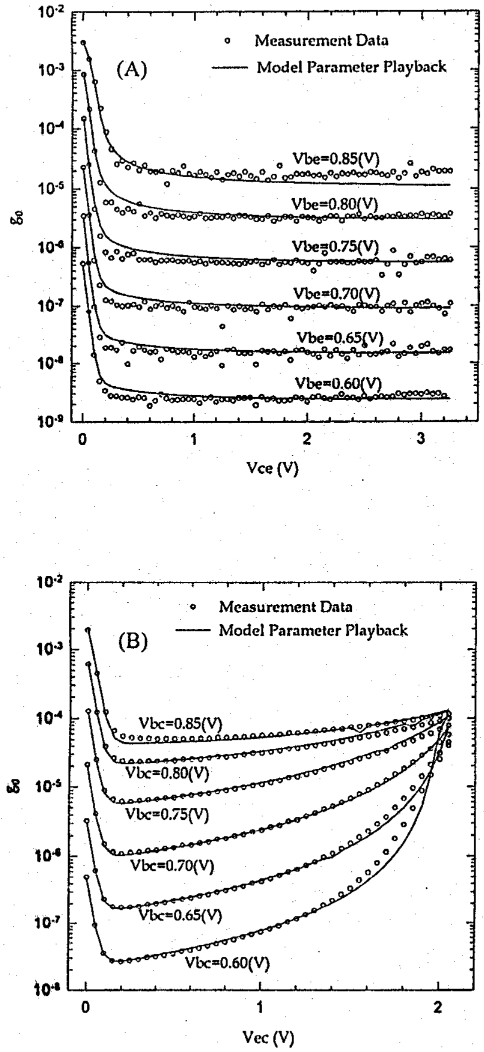


Fig. 6 (a) Forward and (b) reverse output conductance obtained from measurements and from VBIC model using all the parameters extracted.

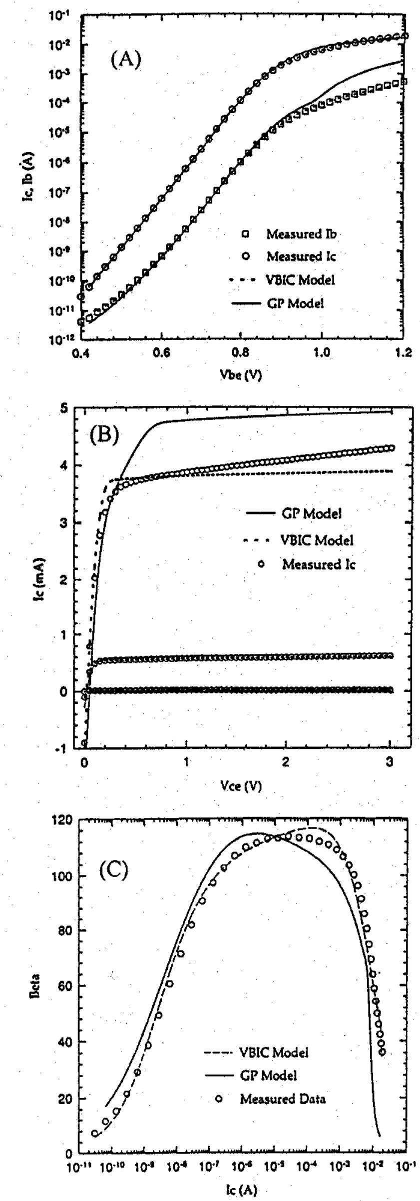


Fig. 7 (a) Gummel plot, (b) current-voltage characteristics, and (c) current gain of the BJT under forward operation obtained from the SGP model, VBIC model, and measurements.

current level and/or is operating at reverse operation.

We want to say a few words regarding the parameters associated with the ac data, which are not extracted in this work. In addition to the dc elements, the VBIC model has more capacitance/charge elements than the SGP model. As a result, the VBIC model, with the coupled dc/ac parameters, can also fit the ac characteristics (i.e., S parameters) much better than the SGP model does. This will be demonstrated in the near future.

## 5. Conclusions

The VBIC model developed recently is likely to replace the SGP model as the industry standard for SPICE circuit simulation of bipolar transistor-based integrated circuits. The use of the advanced features in the VBIC model, however, requires the development of a new parameter extraction and optimization technique. This paper presented such a method by developing a fully automated extraction program coded in S+ statistical language and based on a robust optimization procedure. Advanced bipolar transistors fabricated at Lucent Technologies were measured, and the date were implemented into the method developed to extract VBIC parameters. The results calculated from the VBIC model using the extracted parameters compare more favorably with measurements than the SGP model under various dc and room temperature operation conditions. Extraction of parameters associated with the ac, low temperature, and high temperature operations were not covered in the paper and is a subject of our ongoing and future research.


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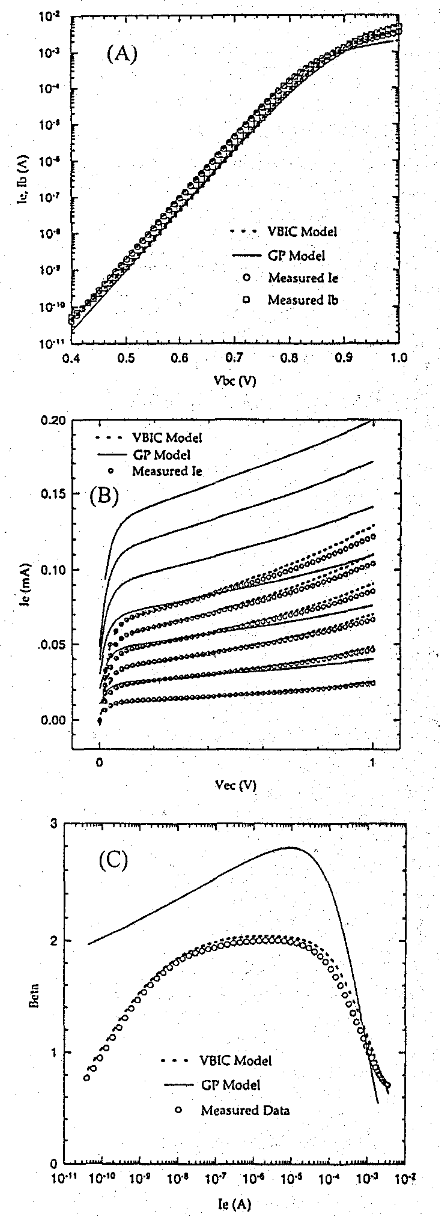


Fig. 8 (a) Gummel plot, (b) current-voltage characteristics, and (c) current gain of the BJT under reverse operation obtained from the SGP model, VBIC model, and measurements.

**References**


[1] I. Getreu, *Modeling the Bipolar Transistor*, New York: Elsevier, 1978.

[2] C. C. McAndrew et al., "VBIC95, the vertical bipolar inter-company model," IEEE J. Solid-St. Circuits, vol. 31, 1996.

[3] G. M. Kull, L. W. Nagel, S. W. Lee, P. Lloyd, E. J. Prendergast, and H. K. Dirks, IEEE Trans. Electron Devices, vol. 32, p. 1103, 1985.

[4] J. A. Seitchik et al., "The determination of SPICE Gummel-Poon parameters by a merged optimization-extraction techniques," Proc. BCTM, 1989.