Microelectronics Reliability 60 (2016) 20–24

Contents lists available at ScienceDirect

Microelectronics Reliability

journal homepage: www.elsevier.com/locate/mr

Analysis of temperature dependence of linearity for SiGe HBTs in the avalanche region using Volterra series

Chie-In Lee [a,b,*], Yan-Ting Lin [a], Wei-Cheng Lin [a]

[a] Department of Electrical Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung 80424, Taiwan
[b] Institute of Communications Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung 80424, Taiwan

A R T I C L E I N F O

Article history:
Received 9 June 2015
Received in revised form 12 September 2015
Accepted 17 November 2015
Available online 1 April 2016

Keywords:
Temperature
SiGe HBT modeling
Avalanche breakdown
Linearity
Volterra series

A B S T R A C T

In this paper, linearity characteristic of silicon germanium (SiGe) heterojunction bipolar transistors (HBTs) at different temperatures in the avalanche regime is investigated by the Volterra approach incorporating with a physics-based breakdown network for the first time. Third-order intermodulation distortion (IMD_3) decreases with increasing temperature in the impact ionization region due to lower nonlinear contributions from individual nonlinearity according to the Volterra analysis results. Calculated gain, output power, and efficiency of SiGe HBTs are in good agreement with measurement results in the avalanche region. This analysis with respect to temperature can benefit the reliability study of linearity for SiGe HBTs in the avalanche regime.

1. Introduction

Characterization of silicon germanium (SiGe) heterojunction bipolar transistor (HBT) linearity at different temperatures is important to radio-frequency (RF) power amplifier (PA) designs because of circuit temperature increment [1,2] during working operation. Over the past years, SiGe HBTs [3–5] have attracted much attention for integrated circuit designs [1,6] due to their high performance at high frequencies. High temperature operation of SiGe HBTs should be investigated to understand the impact of temperature on linearity performance. As silicon-based transistors are applied to PA designs, impact ionization effects [7,8] are needed to be taken into account due to low breakdown voltage. This high field effect is important for reliability issues [9,10] because the device degradation effect on integrated circuits due to impact ionization can be a concern. Temperature dependence on device characteristics for SiGe HBTs had been analyzed in the avalanche and normal regions [4,11]. For circuit designs, linearity performance is one of the important considerations [12]. Circuit linearity primarily depends on device distortion characteristics. Conventionally, a Volterra analysis approach [7,8,12–14] can be utilized to investigate distortion of a transistor such that it can provide information for circuit designers to improve linearity performance of circuits. In addition, interaction between nonlinearities of a transistor which affects linearity performance can be analyzed by Volterra method [7,8,12–14]. In [7,8], Volterra analysis had been employed to investigate device distortion at breakdown. The impact ionization mechanism can be influenced by temperature [15] in addition to electric field. Temperature dependence on linearity performance of SiGe HBTs needs to be further considered since PAs can operate at elevated temperature [1,2].

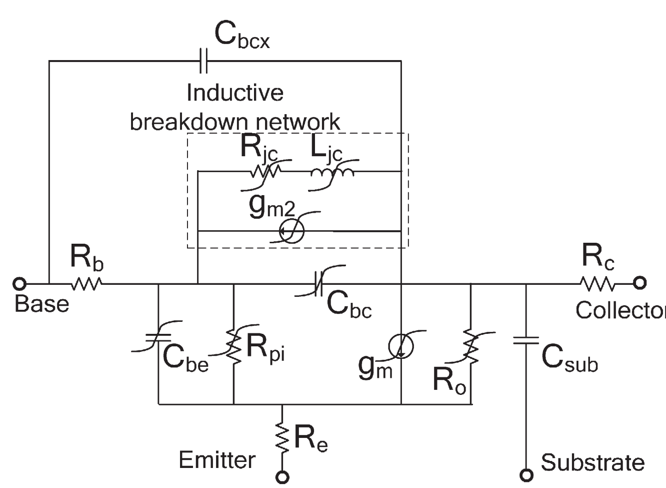

Fig. 1. SiGe HBT nonlinear equivalent circuit model incorporating with the breakdown network utilized for the Volterra analysis at different temperatures. This model is seen to be similar to [7]. However, this work is extended to analyze the temperature dependence on linearity characteristic when compared with Volterra analysis in [7] at room temperature.

* Corresponding author at: Department of Electrical Engineering, National Sun Yat-Sen University, No. 70 Lienhai Rd., Kaohsiung 80424, Taiwan.
E-mail address: chiein@mail.ee.nsysu.edu.tw (C.-I. Lee).

http://dx.doi.org/10.1016/j.microrel.2015.11.011
0026-2714/

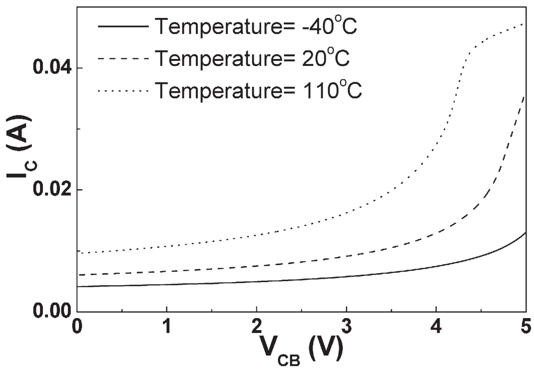

Fig. 2. DC output curve I_C at the V_{CB} from 0 to 5 for different temperatures.

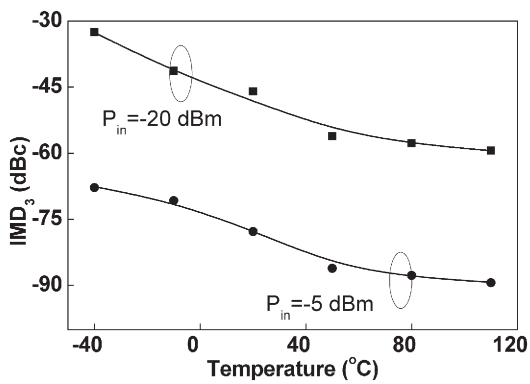

Fig. 3. Measured (symbols) and calculated (lines) IMD_3 versus temperature at $V_{BE} = 1.2$ V, and $V_{CB} = 4.8$ V. The operating frequency is 2.4 GHz.

Our previous research focused on linearity analysis for SiGe HBTs at room temperature in the avalanche region [7]. In this paper, temperature dependence on distortion of SiGe HBTs operating in the avalanche regime is analyzed by using the Volterra approach. According to the analyzed and measured results, better linearity performance at elevated temperature is found for SiGe HBTs in the avalanche regime. This analysis with respect to temperature can benefit the reliability study of linearity for SiGe HBTs in the avalanche regime.

2. Method

The study of transistor avalanche behavior is essential for circuit reliability as mentioned in [16]. The avalanche operation may bring a

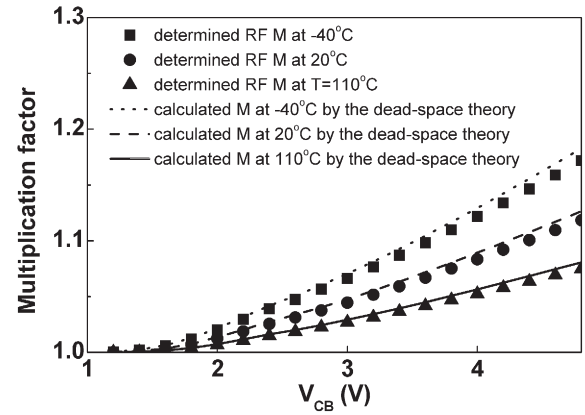

Fig. 5. The determined RF multiplication factor (symbols) and calculated theoretical results (lines) at different temperatures. The theoretical multiplication factor from the dead space theory is calculated by using the typical temperature dependent ionization coefficient [15].

reliability issue for SiGe HBTs due to the high electric field effect [10, 16] as compared with the normal operation. Linearity is the significant performance [12] for transistor analysis and RF circuit design. As a result, this investigation focuses on linearity analysis with respect to temperature in the RF avalanche region where inductive behavior takes places [7] to study whether the avalanche operation is reliable or not. In Fig. 1, the SiGe HBT nonlinear equivalent circuit model for Volterra analysis at different temperature in the avalanche region is shown. When the transistors operate in the avalanche regime in which the reliability is a concern, the impact ionization effect can generate electron–hole pairs in the BC junction. As a high frequency signal is applied, the RF current will lag the RF voltage due to the avalanche delay mechanism in the avalanche regime [7]. The inductive breakdown network consisting of L_{jc} and R_{jc} shown in Fig. 1 describes this RF avalanche delay mechanism at high electric field [7]. In addition to electric field, the impact ionization mechanism can be influenced by temperature [15]. C_{bc} and C_{be} are base–collector and base–emitter junction capacitances, respectively. R_{pi} is base–emitter junction resistance. g_m and R_o are transconductance and output resistance, respectively. g_{m2} is avalanche transconductance. These bias-dependent parameters are regarded as the nonlinear elements in the presented Volterra analysis at different temperature. The standard extrinsic elements include parasitic resistances R_b, R_c, and R_e, collector-substrate capacitance C_{sub}, and base–collector capacitance C_{bcx} for the Volterra analysis of SiGe HBTs [8].

SiGe HBTs fabricated by using the 0.18 μm BiCMOS technology through the Taiwan Semiconductor Manufacturing Company (TSMC), Hsinchu, Taiwan have the emitter area of 1.36 μm^2. The SiGe HBT collector–emitter breakdown voltage with base open (BV_{CEO}) is 4.5 V

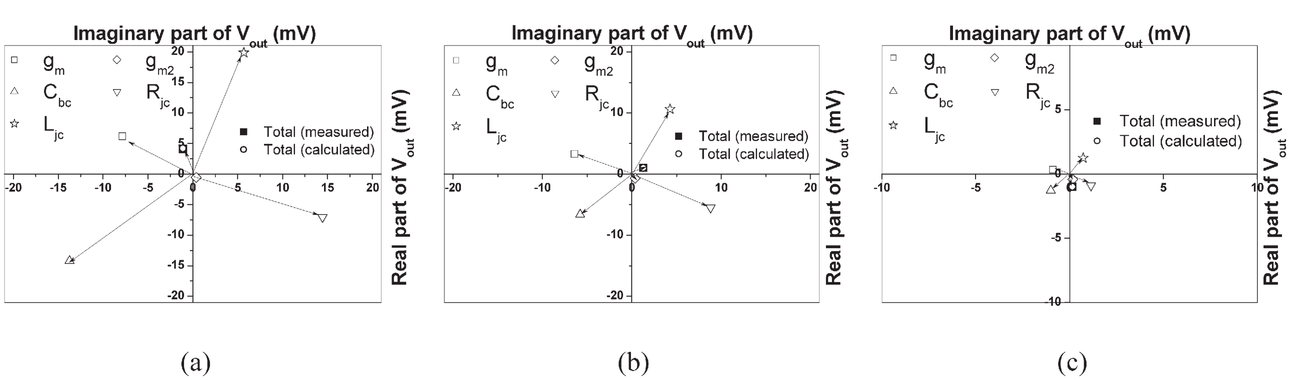

Fig. 4. The vector plot of nonlinear contributions from the individual elements including g_m (open square), g_{m2} (open diamond), C_{bc} (open triangle), R_{jc} (open down triangle), and L_{jc} (open star) at $V_{BE} = 1.2$ V, and $V_{CB} = 4.8$ V. The measured (solid square) and calculated (open circle) total contributions are also shown. (a) Temperature at −40 °C. (b) Temperature at 20 °C. (c) Temperature at 110 °C.