Substrate Effects in Wideband SiGe HBT Mixer Circuits

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Abstract— **In this paper the influence from substrate effects on the performance of wideband SiGe HBT mixer circuits is investigated. Equivalent circuit models including substrate networks are extracted from on-wafer test structures and compared with electromagnetic simulations. Electromagnetic simulations are also applied to predict short distance substrate coupling effects. Simulation results using extracted equivalent circuit models and substrate coupling networks are compared with experimental results obtained on a wideband mixer circuit implemented in a $0.35\,\mu$m, 60 GHz f_T SiGe HBT BiCMOS process.**

I. Introduction

Advanced SiGe HBT technologies make use of a low-doped p substrate with a resistivity in the range of 10-$20\Omega \cdot cm$. In Si-based monolithic microwave integrated circuits (MMICs) this results in a significant high-frequency loading of circuit nodes involving both transistors and passive elements. The non-zero dielectric constant and the conductivity of the Si-substrate may also lead to unwanted coupling between components that otherwise are supposed to operate independently [1].

Equivalent circuit models suitable for predicting the loading due to substrate effects have been presented in [2], while shielding measures to reduce substrate coupling effects have been discussed in [3]-[4]. In the past, however, investigations of the influence of substrate effects in high-frequency integrated circuits have mainly been limited to low-noise amplifiers [5]-[6], and voltage-controlled oscillators [7]. The influence of substrate effects on the frequency response of wideband SiGe HBT mixer circuits has not previously been discussed.

In this paper a combined experimental and simulation study of the effect of the substrate on wideband SiGe HBT circuits is described. Part of the study consists of extracting suitable equivalent circuit models and substrate coupling networks from fabricated on-wafer test structures and electromagnetic simulation. The equivalent circuit models and substrate coupling networks are then used in the simulation of the wideband mixer circuit to investigate the influence on the frequency response. Especially the importance of substrate effects for matching simulations to experimental results obtained on a wideband mixer circuit implemented in a $0.35\,\mu$m, 60 GHz f_T SiGe HBT BiCMOS process will be discussed.

II. Wideband SiGe HBT Mixer Design

A. Circuit Design

The circuit schematic of the wideband SiGe HBT mixer circuit is shown in Fig. 1. It is based on a modified Gilbert cell topology with emitter degenerated transconductance

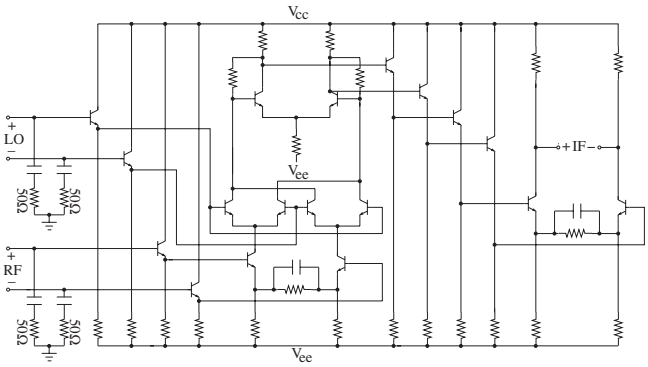

Fig. 1. Circuit schematic of wideband SiGe HBT mixer based on a modified Gilbert Cell topology.

stage and a shunt feedback stage for the load circuit assuring wideband operation at all mixer ports. The principle of strong impedance mismatch is followed throughout the design in order to minimize the influence from parasitics effects. For the wideband SiGe HBT mixer circuit in Fig. 1 certain interconnection lines can be identified as critical for the performance and needs careful consideration [8]. Especially, the interconnection lines providing access to the mixer ports are typical lengthy and needs accurate modeling due to their potential strong effect on the matching properties of the circuit.

B. Interconnection Line Modelling

In SiGe HBT BiCMOS technology, the metal-insulator-semiconductor interconnect line structure results in large capacitance to the substrate. The loss in the substrate can not be neglected at high frequencies and should be taken into account in the modelling of the interconnect lines [9]. Even though the interconnect line in principle is a distributed structure, it is assumed here that a simple π-type model as shown in Fig. 2 is sufficiently accurate to model the behavior of the interconnect line.

The equivalent circuit consist of series resistance and series inductance (R_{LF} and L_{LF}) representing the low frequency ohmic loss and self-inductance of the line. This is followed by a latter network which models the skin effect. The series impedance is shunted by oxide capacitors to the substrate (C_{ox}), and substrate resistances (R_{sub}). Adding shunt capacitors (C_{sub}) across the substrate resistances becomes necessary at higher frequencies to take the transition from the slow-wave mode to the quasi-TEM mode into account [10]. The elements for the interconnect line model are extracted from the admittance parameters for an on-wafer test structure of a thru line de-embedded for pad

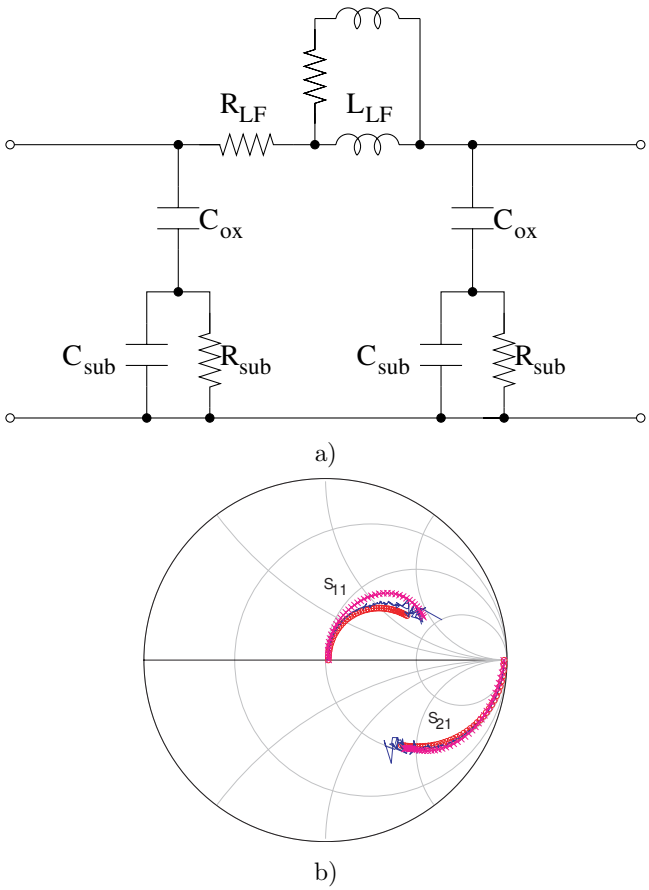

Fig. 2. a) Interconnect line equivalent circuit model. b) Measured (-), modelled (-o-), and simulated (-x-) S-parameters in the frequency range from 45 MHz-40 GHz.

parasitics. The thru line have length 367 μm and width 10 μm and is implemented in the third metal layer located approximately 2.5 μm over the substrate. At low frequencies the series resistance (R_{LF}) and the series inductance (L_{LF}) are extracted as

$$R_{LF} = \Re\left\{\frac{-1}{Y_{12}}\right\} \tag{1}$$

and

$$L_{LF} = \frac{1}{\omega}\Im\left\{\frac{-1}{Y_{12}}\right\} \tag{2}$$

respectively. The remaining elements of the latter network is fittet to the real and imaginary part of the frequency dependent series impedance. The oxide capacitance (C_{ox}) and substrate resistance (R_{sub}) are extracted at sufficiently low frequencies ($\omega \ll 1/(C_{sub}R_{sub})$) as

$$C_{ox} = \frac{-1}{\omega\Im\left\{\frac{1}{Y_{11}+Y_{12}}\right\}} \tag{3}$$

and

$$R_{sub} = \Re\left\{\frac{1}{Y_{11}+Y_{12}}\right\} \tag{4}$$

respectively. The substrate capacitor C_{sub} is extracted as

$$C_{sub} = \sqrt{\frac{C_{ox}^2}{\Re\{Y_{11}+Y_{12}\}R_{sub}} - \frac{1}{\omega^2 R_{sub}^2}} - C_{ox}. \tag{5}$$

Parameter	**Extracted Value** (Measurement)	**Extracted Value** (Momentum)
R_{LF} [Ω]	1.6	1.8
L_{LF} [nH]	0.38	0.42
C_{ox} [fF]	19.4	18.0
R_{sub} [Ω]	251.6	315.4
C_{sub} [fF]	13.6	9.0

TABLE I
EXTRACTED ELEMENTS FOR INTERCONNECT LINE MODEL.

As shown in Fig. 2b) the extracted equivalent circuit model accurately predicts the measured frequency dependent lossy behavior of a interconnection line structure in the frequency range from 45 MHz-40 GHz. The interconnect line structure was also simulated with the electromagnetic simulation tool Momentum in Agilent ADS. As shown in Fig. 2b) the results from the electromagnetic simulation accurately predict the performance of the interconnect line. In Table. I the elements for the interconnect line model are extracted as described above based on either measurement or electromagnetic simulation using Momentum. The excellent agreement between the two approaches shows that the development of scalable models for interconnect lines can confidentially be based upon electromagnetic simulation.

C. Substrate Coupling Modelling

As the frequency of operation rises the coupling into the substrate increases. This may lead to coupling between components which otherwise are supposed to operate independently. It is difficult to design on-wafer test structures suitable for predicting this type of coupling. Instead the substrate coupling between nearby components can be predicted by electromagnetic simulations. In this work, the substrate Green's function as calculated by Agilent ADS Momentum have been used to predict the short-distance substrate coupling. In the Green's function approach the active areas on-chip are abstracted into equipotential substrate ports. Substrate coupling networks between substrate ports can then be extracted [1].

As an example, consider the coupling between a $p+$ guard ring and the collector-substrate junction for a SiGe HBT device as shown in Fig. 3. The layer structure sim-

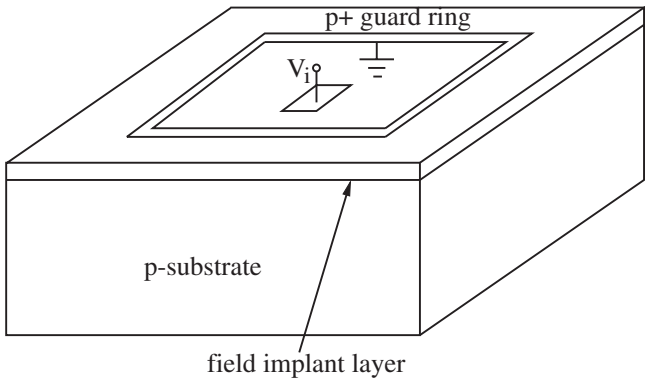

Fig. 3. Example of substrate coupling between $p+$ guard ring and the collector-substrate junction for a SiGe HBT device.

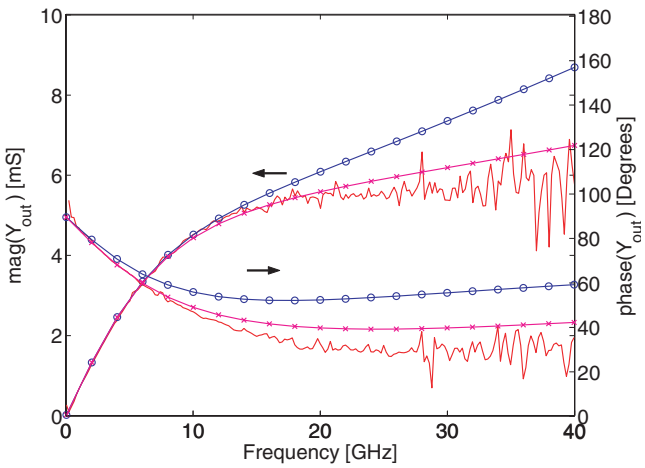

Fig. 4. Influence from substrate coupling network on output admittance for a SiGe HBT device model. Measurements (-), modelled with no substrate coupling network included (-o-), modelled with substrate coupling network included (-x-).

ulated consists of substrate ports on top of a thin p doped field implant layer with resistivity $1\Omega - cm$ followed by a $710\mu m$ thick $p-$ substrate with resistivity of $19\Omega - cm$. In the simulation setup using Momentum, a voltage source excitation V_i is applied to the substrate port representing the collector-substrate junction and the guard ring is grounded using a ground reference port. The admittance parameter simulated can be represented as a shunt RC network. The extracted resistance is around 802Ω and the capacitance is around $3fF$ in good agreement with the values extracted from on-wafer measurements using the method reported in [11]. As a further verification of the above described approach, Fig. 4 shows the improvement in the small-signal output admittance modelling of a $8x0.35\mu m^2$ area SiGe HBT device when including the substrate coupling network found from electromagnetic simulation.

III. Experimental Results

The circuit was realized in a 0.35μm, 60 GHz f_T SiGe HBT BiCMOS process. The photograph of the fabricated wideband SiGe HBT mixer circuit is shown in Fig. 5. The current consumption was 61 mA from a ± 2.5 V supply. The characterization of the circuit were performed using on-wafer measurements. In order to investigate the influence from substrate effects on the frequency response of the wideband SiGe HBT mixer circuit two levels of simulation complexity are compared. The first level is a nominal simulation including only SiGe HBT devices, poly resistors and MIM capacitors. This level of simulation complexity corresponds to what is normally possible with standard SiGe HBT foundry process design kits. In the nominal simulation the substrate networks for all components are neglected. The second level of simulation complexity takes the pads, critical interconnect lines, and substrate coupling networks associated with SiGe HBT devices, poly resistors, and MIM capacitors into account. The SiGe HBT devices are modelled using the VBIC95 model with the substrate terminals interconnected through the substrate coupling network found from electromagnetic simulation.

As shown in Fig. 6 the high frequency roll-off observed

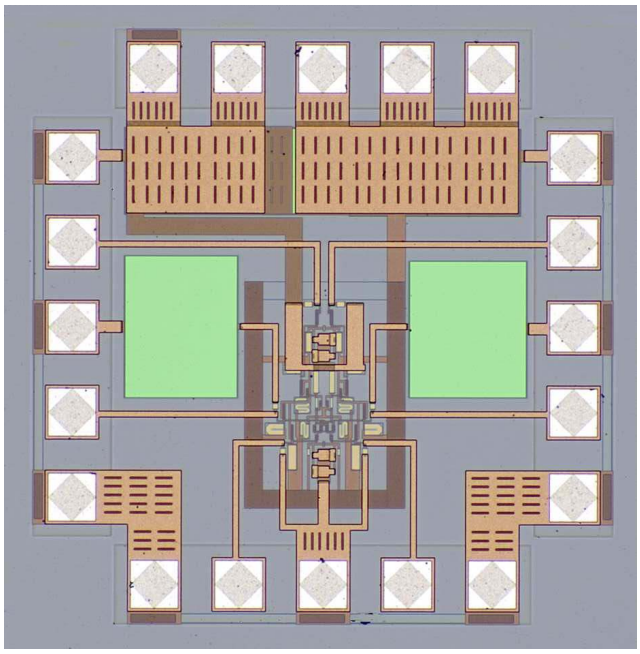

Fig. 5. Photograph of wideband SiGe HBT mixer ($0.9x0.9mm^2$).

in the measured conversion gain is more closely matched by simulations when the pads, critical interconnect lines, and substrate coupling networks are properly taken into account. The remaining difference is believed to be due to the accumulated influence from interconnection lines not yet accounted for in the simulation. Fig. 7 shows the double sideband noise figure for the wideband active mixer. It is observed that the nominal simulation underestimates the noise figure at higher frequency while the complex simulation more accurately captures the increase in noise. It is observed however, that the noise figure seems to be less sensitive to substrate effects than the frequency response of the conversion gain.

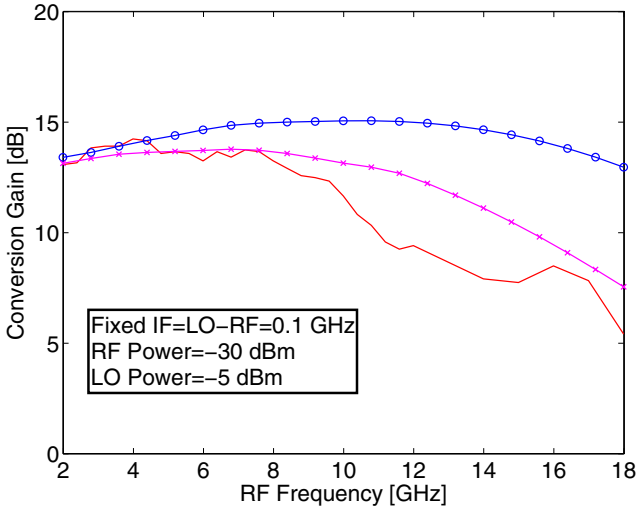

Fig. 6. Comparing measured (-) conversion gain with nominal simulation (-o-) and simulation with substrate networks included (-x-).

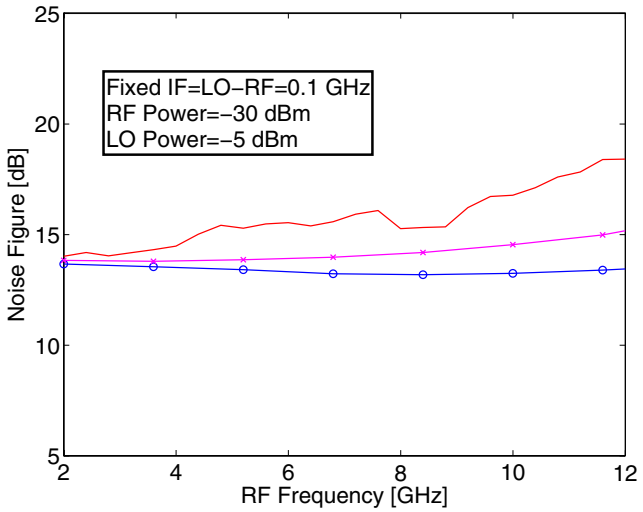

Fig. 7. Comparing measured (-) double-sideband noise figure with nominal simulation (-o-) and simulation with substrate networks included (-x-).

IV. Conclusion

In this paper an investigation of substrate effects on the frequency response of wideband SiGe HBT mixer circuits was reported. As part of the investigation, equivalent circuit models and substrate coupling networks were extracted from on-wafer test structures and electromagnetic simulation. Nominal simulations fails to predict the roll-off rate in the conversion gain and the increase in double sideband noise figure at high frequencies. Inclusion of parasitic effects comprised of the extracted substrate networks were found increasingly important at higher frequencies for the prediction of measured results with simulations.

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