Comparison of noise predictions by commercial TCAD device simulator to results from a spherical harmonics expansion solver

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Abstract— **A systematic comparison between commercial TCAD and dedicated academic tools for noise modeling was performed. It was proven that the hydrodynamic model in the Sentaurus device simulator can reliably reproduce the high-frequency noise in state-of-the-art SiGe HBTs. The role of stress has also been analyzed, where devices with an additional uniaxial stress was shown to have better noise performance compared to the normal devices without stress.**

Keywords: drift diffusion, hydrodynamic, Boltzmann equation, spherical harmonic expansion, noise, SiGe HBT, uniaxial stress

I. INTRODUCTION

In recent years, there has been great interest in improving the RF noise performance of cost-effective SiGe heterojunction bipolar transistors (HBT) to be able to replace expensive GaAs transistors currently used in high-performance low noise amplifiers [1]. One of the most challenging tasks during any process and device optimization in terms of noise performance is to be able to get reliable noise results with the least effort and time; e.g. direct verification of the impact of layout and/or process variations on the noise level. There have been many undertakings to tackle this problem [2]. Within NXP Semiconductors, techniques for fast noise prediction by only standard DC and S-parameters measurements [3] as well as advanced macroscopic modeling techniques [4] have been successfully developed. However, in some situations, they are still cumbersome and time-consuming involving complex scaling or resistance extraction procedures. Moreover, it is not trivial for this modeling tool to predict the noise for devices with complicated physical effects. An example is the presence of uniaxial stress, either from an intentional force (e.g. wafer bending) [5-6] or from the back-end stack [7]. Microscopic noise modeling in TCAD appears to be a complementary tool to overcome these difficulties.

Although commercial TCAD has been widely adopted throughout the industry, its use for noise predictions seems fairly limited, which might be due to doubts of TCAD's credibility in this area and/or difficulties in verifying and choosing suitable device-simulation models (e.g. Drift diffusion versus Hydrodynamic). On the other hand, it has been proven that TCAD can indeed provide reliable noise data, by means of dedicated device simulators for noise modeling that have been developed by, and are being used in, academia [8]. Industry seems hesitant to adopt such new tools due to reasons such as lack of maintenance and support. To bridge the gap between both TCAD environments, it is necessary to work out a systematic way for verifying the capability of noise simulation of commercial TCAD programs.

In this work, we show by a systematic investigation, that we can verify the capability of noise simulation of Sentaurus device simulator (Sdevice) [9] for state-of-the-art SiGe HBTs. NXP BICMOS technology, QUBIC, is used as input for our TCAD deck. Here, both drift diffusion (DD) and hydrodynamic (HD) models are used. The simulation results from these models are compared with measurements as well as with the Spherical Harmonics Expansion of the Boltzmann equation (shortly named SHE) [10]. Since SHE solves the Boltzmann equation directly and includes all parameters from full-band Monte Carlo (FB-MC), it can predict the noise accurately for advanced devices. Finally, the noise performance of uniaxially stressed SiGe HBTs is investigated by Sdevice, in comparison with SHE.

II. MICROSCOPIC NOISE SIMULATION FOR BIPOLAR TRANSISTORS

Microscopic (or physic-based) noise simulation is the evaluation of the fluctuations at the device terminals induced by the fundamental velocity and population fluctuations occurring throughout the device volume [11-12]. There are two main microscopic noise sources in a device: diffusion noise source resulting from carrier velocity fluctuation (or current density fluctuation) and generation-recombination (GR) noise from the fluctuation of carrier numbers (or charge fluctuation).

With this approach, noise sources are modeled by a Langevin stochastic source term, which is incorporated into the equations for device simulations of the DD or HD model [13-15]. Then the noise density at the terminals is calculated from the noise source at each point inside the device by a space convolution whose kernel is a Green’s function. This method is commonly called *impedance field method* [12], which has been implemented in Sdevice (for both DD and HD) for noise simulation [9].

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Although the HD model is more advanced than DD for device simulation (e.g. nonlocal effects are taken into account in HD), it has also limitations e.g. overestimating cutoff frequency (f_T) or maximum oscillation frequency (f_{MAX}). A recent investigation of such problems for advanced MOSFETs has been reported in [16]. For bipolar transistors, those limitations of the HD model have been addressed comprehensively in [17-19]. In those works, the authors adjusted HD parameters including energy flux, heat flux and thermal diffusion for a better prediction of f_T/f_{MAX}. However, the impact of varying these parameters on the noise behavior was not investigated. As we know, changing these parameters has a large impact on Joule heating which, in turn, affects strongly the noise performance of the devices. Therefore, in this work, these parameters are kept unchanged.

For the purpose of a systematic comparison, the consistency among various simulators is very important. It is for sure that the difference in simulation results from different simulators is due to the model itself, not to any other factor. Therefore, all simulators use the same transport parameters including band gap, mobility (low field and high field) and saturation velocity which have been extracted from full-band Monte Carlo simulations.

III. NOISE SIMULATIONS FOR QUBIC DEVICES

A. Device structure and RF performance

In this work, we have done 2D simulations for a SiGe HBT device, whose vertical profile is similar to the one shown in [1].

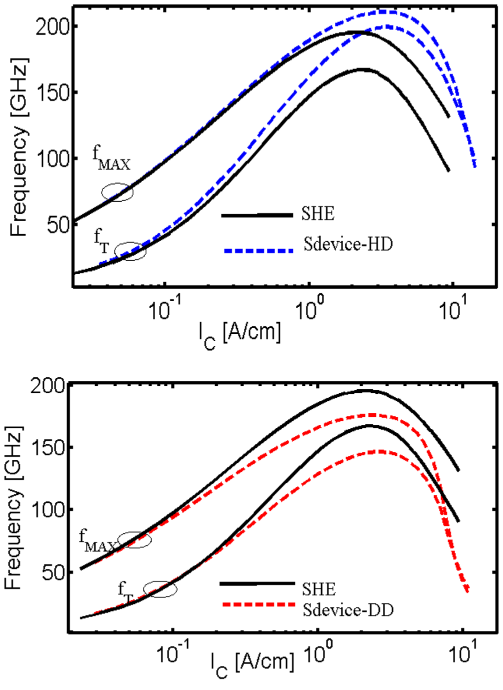

Fig. 1: Comparison of f_T and f_{MAX} simulated with Sdevice and SHE: (upper) HD; (lower) DD at V_{CE}=1V.

RF performance of this device including f_T/f_{MAX} are simulated and compared among different simulators (Sdevice-HD/DD and SHE), as shown in Fig. 1. As commonly expected, DD underestimates f_T/f_{MAX} and HD overestimates these quantities (since we do not change HD parameters as mentioned in Sec. II).

B. Noise at device terminals

Firstly, the spectral density of noise at the base (S_{I_B,I_B}) is simulated. Both HD and DD models produce the noise results as expected, from low to high frequencies, following this formula [13]

$$S_{I_B,I_B} = 2q\,|\,I_B\,| + 4k_BT_0\Re\{Y_{B,B}(\omega) - Y_{B,B}(\omega=0)\} \qquad (1)$$

where $Y_{B,B}$ is the base self-admittance (or Y_{11} in a 2-port configuration). Fig. 2 shows the agreement between $S_{IB,IB}$ obtained from simulations and calculated directly from (1) over a wide range of frequencies.

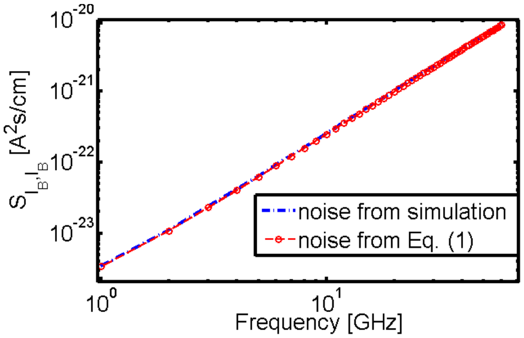

Fig. 2: Spectral intensity of the base current fluctuations at different frequencies (for both HD and DD) at V_{BE}=0.8V.

Secondly, the noise at the collector is investigated. Its spectral density is calculated by [13]

$$S_{Ic,Ic} = 2q\,|\,I_C\,| + 4k_BT_0R_{B,n}\,|\,Y_{C,B}(\omega)\,|^2, \qquad (2)$$

where $Y_{C,B}$ is the collector-base admittance (or Y_{21} in a 2-port configuration) and $R_{B,n}$ is the equivalent noise resistance of the base, which can be determined from device simulation as presented in [14]. At low current density and low frequency, $S_{IC,IC}$ becomes $2q|I_C|$. However, as reported in [15], there is a discrepancy between HD and DD at predicting noise at the collector for modern SiGe HBTs (e.g. SiGe HBTs with a thin base in the order of tens of *nm*). Here, such investigation has been done again with Sdevice. In fact, similar results are reproduced here: DD overestimates the noise of the collector (in Fig. 3).

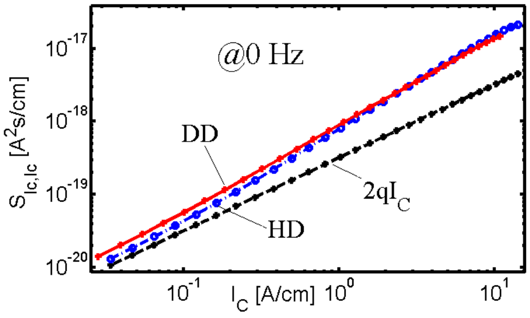

Fig. 3: Spectral intensity of the collector current fluctuations at 0Hz evaluated by Sdevice-DD/HD.

This failure of the DD model in simulating the noise at the collector was attributed to the failure of the DD approximation itself in the condition of near-ballistic transport [15]. In this work, to reconfirm this explanation with Sdevice, two following conditions have been checked: a SiGe HBT with a thick base (e.g. up to $1\mu m$) or a normal device (thin base) with saturation velocity turned off. It turns out that under these conditions, when the DD approximation is valid, the spectral noise density at low current density indeed reduces to $2qI_C$ (shown in Fig. 4).

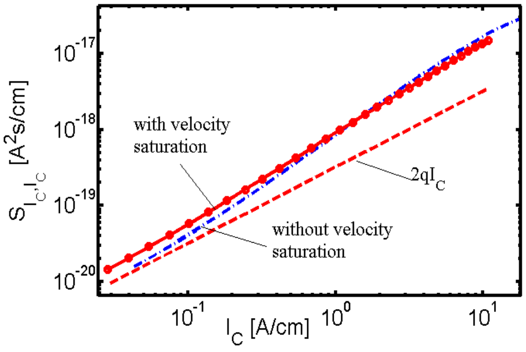

Fig. 4: Spectral intensity of the collector current fluctuations at 0Hz for a normal SiGe HBT (thin base) evaluated by Sdevice-DD with and without velocity saturation.

C. Comparison with SHE and measurements

In this part, minimum noise figure *NFmin*, noise resistance *Rn* and associated gain *Gass* from Sdevice-HD are compared with SHE and measurements. The simulations have been done from 1 to 60 GHz.

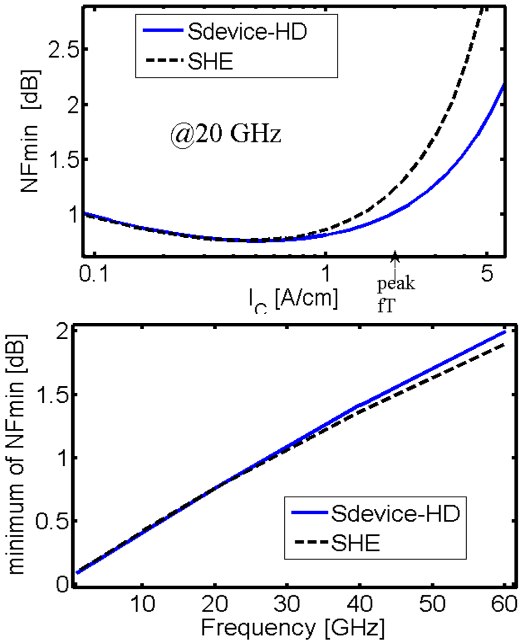

Fig. 5: A comparison of NFmin between Sdevice-HD and SHE simulations: (upper) at 20 GHz; (lower) minimum of NFmin over different frequencies.

Fig. 5 shows the *NFmin* at 20 GHz obtained from HD and SHE. HD can predict the same noise results as SHE at low collector currents. Even though there is a discrepancy at higher currents, it might be of no interest for most applications (above peak-f_T region). The same behavior has been observed for *Rn* and *Gass* (not shown here). A reasonable agreement between SHE and HD over a wide range of frequencies is obtained.

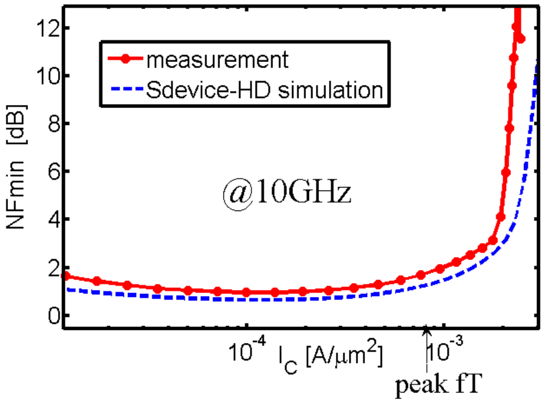

Fig. 6: A comparison of NFmin at 10 GHz between Sdevice-HD simulations and the noise measurements.

Finally, the simulations are compared with measurements. To be able to do that, we have done simulations for a more complicated 2D structure, which is created from TCAD process simulation (vertical profile is still the same as in [1]). This TCAD deck has been well calibrated with measurements (for DC and AC characterization). Fig. 6 shows the comparison of *NFmin* obtained from HD simulations and measurements, where a good agreement is observed, especially at the condition around the minimum of *NFmin*.

IV. NOISE PERFORMANCE FOR STRESSED DEVICES

In this part, the noise performance for the device mentioned previously but with a global additional uniaxial stress is investigated. Such a device is illustrated in Fig. 7. Since there have been strong indication of the presence of such type of stress in common BiCMOS process, originating from shallow trend isolation (STI) [20] or being induced from the back-end [7], it is useful to model the impact of stress on device performance.

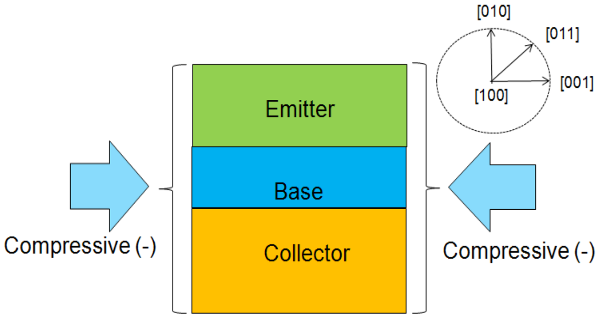

Fig. 7: Schematic 1D diagram of the SiGe HBT device under a global additional uniaxial stress [4].

Although RF performance of the device with stress has been studied [4], its noise performance has not been investigated. In this work, SHE and Sdevice - HD are used to simulate its RF noise. The 2D simulations take into account the change of band gap and band edges of the alloy SiGe as well as the shifts of different valleys under the impact of a uniaxial stress.

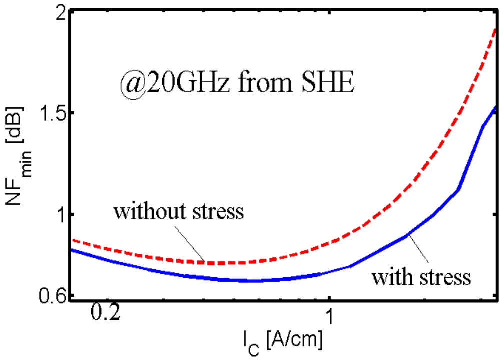

Fig. 8: NFmin (at 20 GHz) obtained from SHE simulations for the stressed device (1 GPa compressive stress along [010] direction) in comparison with that of the unstressed one.

Fig. 8 shows the noise performance at 20 GHz for the device without and with a compressive stress of 1 GPa along [010] direction. The noise figure is reduced at all collector currents for the stressed device.

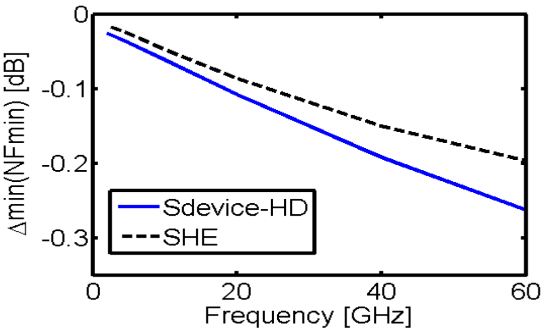

Fig. 9: The change of min*(NFmin)* under an additional stress of -1GPa along [010] direction:

$$\Delta \min(NF\min) = \min(NF\min(stress)) - \min(NF\min(without\_stress))$$

Finally, the change of the minimum of *NFmin* over different frequencies due to that stress is shown in Fig. 9 for both SHE and HD simulations. HD predicts the same trend as SHE, from low to high frequencies. And quantitatively, the agreement between them is also reasonable. A better agreement could have been obtained with a finer tuning of the band structures used in Sdevice to those used in full-band Monte Carlo (which is calculated from empirical pseudo potential method).

V. CONCLUSION

Through a systematic way of investigations, it has been shown, that the HD model from Sdevice can be used for investigating the noise performance of state-of-the-art SiGe HBTs. This model proves to give comparable results to dedicated academic noise modeling tools as well as experimental data. In addition, it was shown that stress has a non-negligible effect on the noise performance. The capability of Sdevice to include the effects of stress opens up the possibility to further optimize SiGe HBTs by strain engineering.

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