Nonequilibrium transport in GaAs Schottky mixers at 2.5 THz

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Abstract. This work presents an analysis of the electrical and the noise performances of a 2.5 THz mixer. Reliable and self-consistent simulations of the circuit are carried out by means of a Monte Carlo model of the diode coupled to a harmonic balance technique. Simulations with this tool have shown that hot electrons and intervalley transitions can highly degrade the performance of this mixer. Additionally, these phenomena can be mitigated by decreasing the epilayer length of the diode.

1. Introduction

Schottky diodes are one of the most used devices for applications at terahertz frequencies such as Earth observation, planetary science, medicine, security, etc. These devices have the advantage over other sensor technologies to work at room temperature with good sensitivities [1, 2]. Actually, planar GaAs Schottky-based mixers operating at frequencies up to 2.5 THz have been designed and fabricated [3].

Physics-based modeling of the carrier transport in semiconductor devices is essential to understand and optimize the performance of nonlinear circuits at millimeter and submillimeter wavelengths. At these high frequencies, the electrical response of the diodes is limited by different physical phenomena such as velocity saturation, nonlocal or plasma effects among others. In addition, the noise performance of the diode is mainly degraded due to the presence of hot electron noise and intervalley scattering events. An accurate and reliable description of these phenomena requires high level physics-based models like the Monte Carlo model which provides a unified and self-consistent description of the electrical and noise performances of the diode.

This work presents an analysis of the carrier transport in the diode of the 2.5 THz receiver [3] and its impact on its two main figures of merit, i.e. the conversion losses and the equivalent input noise temperatures. To carry out this task, we have developed a compact simulator based on a multi-tone harmonic balance (HB) technique [4] coupled to a Monte Carlo (MC) model of the diode [5] (denoted by MCHB). This tool avoids the need of any additional analytical or empirical model to carry out physics and circuits optimizations of the mixer.

2. Description of the simulation tool

This section presents a brief description of the structure of a Schottky receiver and the simulation tool used in this work to calculate the conversion losses and noise temperatures of this circuit.

A Schottky receiver is composed of different elements which contribute to the conversion losses and noise temperature of the circuit. The total conversion losses of the receiver L_{rec} are:

$$L_{rec} = L_{qo} L_{rf} L_d L_{if}, \tag{1}$$

where L_{qo} represents the losses in the quasi-optical parts of the systems (lens, diplexers, etc.), L_{rf} represents the losses in the feed-horn, filters and mixer waveguides, L_d are the diode conversion losses, and L_{if} are the resistive and mismatch losses in the IF matching circuit [1, 6]. By using the Friis' formula, the equivalent input noise temperature of the receiver is:

$$\begin{aligned} T_{rec,DSB} = (L_{qo}-1)T_0 + L_{qo}(L_{rf}-1)T_0 + L_{qo}L_{rf}T_{d,DSB} + L_{qo}L_{rf}L_{d,DSB}(L_{if}-1)T_0 \\ + L_{qo}L_{rf}L_{d,DSB}L_{if}T_{if} = (L_{qo}-1)T_0 + L_{qo}T_{mix,DSB} + L_{qo}L_{mix,DSB}T_{if} \end{aligned} \tag{2}$$

where DSB and SSB mean double and single sideband, respectively, ($L_{d,SSB}(dB) = L_{d,DSB}(dB) + 3\,dB$ and $T_{d,SSB}(K) = 2T_{d,DSB}(K)$ have been assumed [6]), T_0 is the physical temperature, T_d is the diode noise temperature, and T_{if} is the noise temperature of the IF chain. L_d and T_d are calculated with our MCHB simulator, [7]. Then, L_{rec} and T_{rec} are evaluated using (1) and (2), and the data provided in the literature for L_{qo}, L_{rf}, L_d, L_{if} and T_{if} [7].

Our circuit simulator is based on a HB technique properly adapted for multi-tone excitations, coupled to a self-consistent MC model of the diode [7]. The MC model [5] is based on the microscopic simulation of the electron transport in the semiconductor, providing a reliable description of the electrical and noise performances of the devices. Shot noise, thermal noise, hot electron noise and intervalley scattering noise as well as the effects due to the modulation of the noise sources by the voltage waveforms are inherently taken into account with this method. The multi-tone HB takes into account the different intermodulation products of the LO and the RF signals, ($mf_{LO} + nf_{RF}$, where m and n are integers, and f_{LO} and f_{RF} are the LO and RF frequencies, respectively). It uses the fast Fourier transforms when f_{LO} and f_{RF} are commensurate and the almost periodic Fourier transforms when they are not [6].

3. Analysis of a 2.5 THz mixer

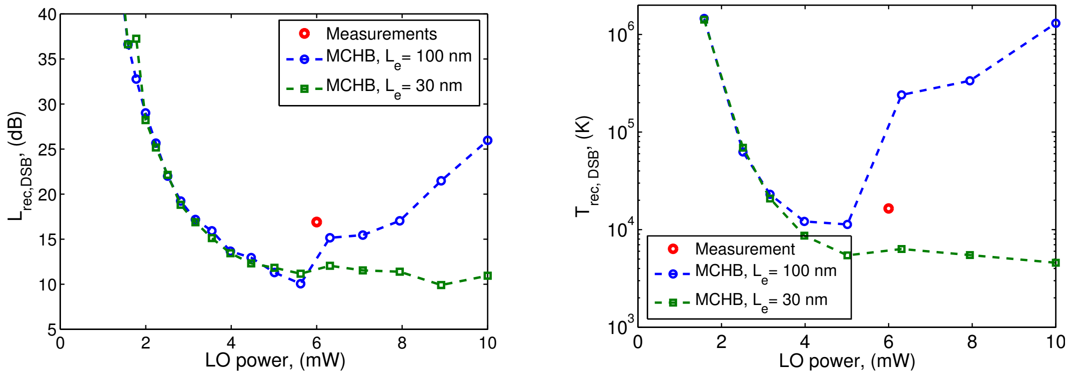
This section presents an analysis of the performance of the single-ended fundamental 2.5 THz mixer presented in [3], see table 1. This mixer has been selected as a representative example to analyze the impact of the high frequency physical phenomena in the performance of the circuit. Some parameters of the mixer [3] like the ideal barrier height of the diode ϕ_b, the bias voltage V_{bias}, and circuit impedances are not provided in the literature, see table 1. In the simulations, ϕ_b and V_{bias} have been selected according to typical values for GaAs mixers and the circuit impedance at the LO, RF and IF frequencies have been optimized with the MCHB tool to minimize the conversion losses at the available LO power P_{LO}= 5 mW indicated in [3]. According to [3], L_{qo}= 2 dB, L_{if}= 0.4 dB and T_{if}= 150 K (L_{rf} is not provided in [3] and L_{rf}= 0 dB has been assumed in the simulations).

Figure 1 shows L_{rec} and T_{rec} of the 2.5 THz mixer simulated with the MCHB tool. In order to optimize the performance of the mixer, a diode with epilayer length L_e= 30 nm has been also simulated (L_e= 100 nm in [3]). Some discrepancies between measured and simulated results are observed, due to the indicated uncertainties in some parameters of the mixer.

L_{rec} for the mixer with L_e= 100 nm in figure 1(a) shows an abrupt increase at LO power around 6 mW (flat band conditions are achieved at LO power around 4 mW). According to MCHB simulations, the occupation of the L valley is around 5 % at P_{LO}= 2.5 mW, and 20 % at 5 mW, rising quickly up to 60 % at 6.3 mW, see figure 2(a). In addition, when the LO power

Table 1. Parameters used in the simulation of the 2.5 THz fundamental mixer. Data in bold type are provided in [3]. $f_{IF} = f_{RF} - f_{LO} = 25$ GHz has been selected to speed up MCHB.

Circuit parameters		Diode parameters	
RF frequency, f_{RF}, (GHz)	**2500**	Epilayer doping, N_e, (cm^{-3})	**1x10^{18}**
LO frequency, f_{LO}, (GHz)	2475	Epilayer length, L_e, (nm)	**100**
Bias voltage, V_{bias}, (V)	0.6	Area, (μm^2)	**0.35**
Circuit impedance at f_{RF}, Z$_{RF}$, (Ω)	70+j113	Ideal barrier height, ϕ_b, (V)	0.99
Circuit impedance at f_{LO}, Z$_{LO}$, (Ω)	86+j36	Series resistance, R_s, (Ω)	20.3
Circuit impedance at f_{IF}, Z$_{IF}$, (Ω)	250	Junction capacitance, $C_j(0)$, (fF)	1.1



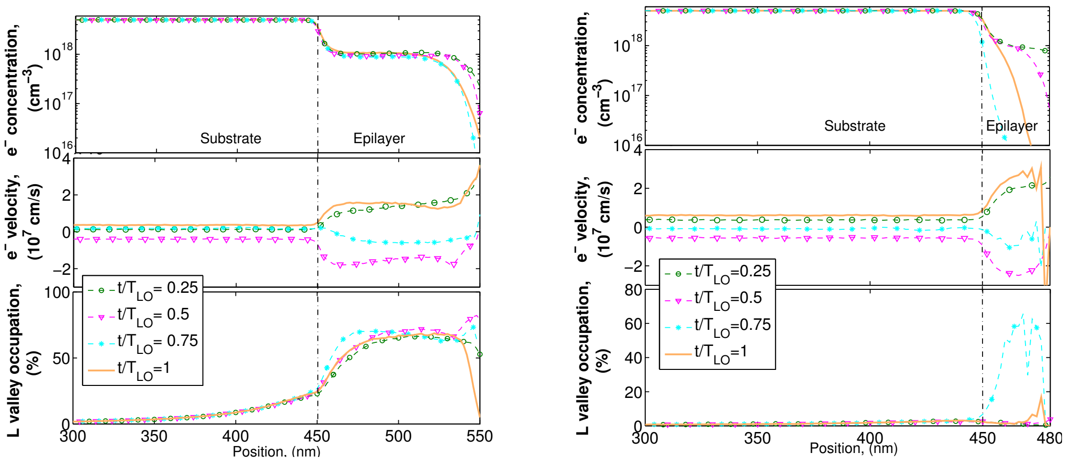
(a) (b)

Figure 1. (a) $L_{rec,DSB}$ and (b) $T_{rec,DSB}$ of the 2.5 THz fundamental receiver in [3] with epilayer length L_e= 100 nm [3] and 30 nm. Simulated results obtained with the MCHB tool.

is increased from 5 mW to 6.3 mW, the occupation of the X valley increases from values lower than 5 % up to 20 %. These data suggest that the abrupt increase of L_{rec} is due to velocity saturation effects originated by the occupation of the upper low mobility valleys (L and X in GaAs) in the undepleted region of the epilayer. Figure 1(b) shows a significant degradation of the noise temperature of the mixer with L_e= 100 nm at P_{LO} higher than 4 mW. As the LO power increases, the energy of the electrons in the undepleted epilayer of the diode increases with respect to the equilibrium value, leading to hot electron noise. When the energy of the electrons is high enough for intervalley transfer to take place, the stochastic transitions between the lowest and upper valleys of the semiconductor generate an additional contribution to the noise spectrum usually known as intervalley scattering noise. The abrupt increase of the noise temperature in figure 1(b) for the diode with L_e= 100 nm at P_{LO} around 6 mW is due to the quick increase of the intervalley transfer at these powers (as it has been depicted in figure 2 (a)).

In order to optimize the performance of the 2.5 THz mixer, the epilayer length of the diode has been set to 30 nm. Figure 1 shows that L_{rec} and T_{rec} for the mixer with L_e= 30 nm do not present the abrupt increases observed for the mixer with L_e= 100 nm. There are three important phenomena which cause this enhancement of L_{rec} and T_{rec} in the optimized mixer:

- The epilayer is totally depleted during a high temporal fraction of the LO period, see figure 2(b), mitigating velocity saturation effects.
- The electrons that come from the substrate (low field region) enter into the epilayer (high field region), where they move with a velocity higher than expected from the steady-state velocity-field curve (nonlocal transport).



(a) (b)

Figure 2. Profiles of the electron concentration, the electron velocity, and the occupation of the L valley for the 2.5 THz mixer with (a) L_e= 100 nm, and (b) L_e= 30 nm at P_{LO}= 6.31 mW. Results obtained with the MCHB tool at different time instants in a LO period (T_{LO}).

- The mean free path of the electrons in the epilayer is of order of the epilayer length, and hence, electron transport is strongly affected by ballistic carriers.

Due to these phenomena, for a long time of the period of the signal most of the electrons in the epilayer of the diode with L_e= 30 nm remain in the Γ valley, see figure 2(b), leading to L_{rec} and T_{rec} nearly constant at P_{LO} higher than 4 mW, see figure 1.

4. Conclusion

An accurate Monte Carlo harmonic balance circuit simulator has been used to analyse the electrical and the noise performances of a 2.5 THz mixer. It has been shown that velocity saturation limits the conversion losses of this mixer. In addition, the generation of hot electrons and intervalley transfer degrade its noise temperature. Nonlocal transport and ballistic transport in short epilayers have demonstrated to mitigate these limiting phenomena, leading to an important enhancement of the performance of the mixer.

Acknowledgments

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