InGaAs Schottky technology for THz mixers

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Abstract— This paper presents a theoretical analysis of the capabilities of InGaAs Schottky diodes as mixers in the THz band. InGaAs diodes are interesting because of their low barrier height compared with GaAs diodes, which yield a reduction in required LO power. In order to provide a reliable and accurate description of the electrical and noise performance of InGaAs mixers, a Monte Carlo model of the diode coupled to a multi-tone harmonic balance technique has been used in this work. Progress towards the development of THz InGaAs Schottky diode mixers at STFC-RAL Space is also presented.

I. INTRODUCTION

GaAs Schottky barrier diode frequency mixers are used in Earth observation and planetary science heterodyne receivers and wider applications such as security imaging and non-destructive testing of materials. Schottky mixers offer good sensitivity in the THz band with the important capability of operation at either room or cryogenic temperatures. An important drawback of these devices is the higher level of required local oscillator (LO) power when compared with superconducting mixer equivalents, an attribute that is exacerbated as the frequency of operation increases [1, 2]. As a means of LO power mitigation, Schottky mixers can be configured as sub-harmonically pumped (SHP) devices and for which the LO frequency is one half that of the signal to be detected. Additionally, DC biasing of the diode can be introduced, though this challenging to implement at frequencies above ~1THz. Despite these development strategies, mixer LO power generation remains a significant issue, particularly for spaceborne applications, with requirements typically in excess of a few mW above 1 THz.

Addressing the above limitation requires an examination of the properties of the Schottky barrier formed at the semiconductor-mental junction interface. By use of an alternative semiconductor material to GaAs, for example InGaAs, a reduction in the barrier height can be achieved and this, in turn, lowers the point at which the mixing action occurs, i.e. the LO power required to effectively pump the diode is reduced [3, 4]. This allows a simplification of the device embedding circuity since the InGaAs does not need to be biased and thereby assisting with higher frequency implementation. InGaAs SHP mixers at 183 GHz have been previously demonstrated and have achieved a conversion loss of 6.6 dB and noise temperature of 700 K with only 0.34 mW applied LO power. When compared with the equivalent state-of-the-art GaAs mixer performance of 5.7 dB and 450 K respectively [5], the InGaAs sensitivity is inferior. But, the low power required for the GaAs is almost an order of magnitude higher and places considerable demands on the LO generation scheme. The performance of InGaAs Schottky mixers at higher frequencies has not, however, been demonstrated and only numerical results based on simple lumped equivalent circuit models of the diode and the conversion matrix formalism are available [3, 4]. It is known that these simulation tools are limited in their capability to model the electrical and noise performance of the InGaAs diode at high frequencies.

This paper reports on progress towards the development of THz InGaAs Schottky diode mixers at the STFC-RAL Space Millimetre Wave Technology group (MMTG). Monte Carlo (MC) modelling of the diode together with a multi-tone harmonic balance (HB) technique have been used to provide an accurate and reliable description of the electrical and noise performances of InGaAs mixers above 1 THz. The DC characteristics of InGaAs diodes fabricated at the MMTG will be presented.

II. MODELLING OF INGAAS DEVICES

In order to develop THz InGaAs circuits, it is fundamental to model accurately the electrical and noise performances of the InGaAs diode at high frequencies. The design of THz Schottky circuits is usually carried out using simple lumped equivalent circuit models of the diode where the diode parameters are set based on experimental results. This modeling strategy is not available for InGaAs based circuits because of the lack of experimental knowledge of InGaAs diodes at the THz band [5, 6].

In this work, we have use a Monte Carlo model of the diode developed by the Tor Vergata University to describe the performance of the diode. The MC model provides a unified and self-consistent description of the electrical and the noise performances of the device without the necessity of any additional analytical or empirical model. This model provides a solution for the Boltzmann transport equation by simulating the trajectories of individual carriers as they move through a device under the influence of electric fields and random scattering forces [7]. Therefore, this technique provides an accurate description of physical phenomena in the device up to THz frequencies.

The MC model has been successfully used to model the performance of devices under high frequency conditions for several semiconductors, GaAs and InGaAs among them [7, 8, 9]. In order to simulate mixer circuits, the MC diode model has been coupled to a multi-tone harmonic balance (MCHB). This simulation tools allows evaluating the conversion loss and noise temperature of mixers as described in [9].

A. Electrical performance of InGaAs diodes

The selection of the *In* fraction in the InGaAs semiconductor has an important impact on the electrical properties of the semiconductor, and therefore, on the performance of InGaAs circuits. According to the experimental results in [10, 11], the low field electron mobility of InGaAs increases as the *In* fraction increases which contributes to reduce the series resistance of the InGaAs devices. On the other hand, the higher the *In* fraction, the lower the ideal barrier height ϕ_b of a Schottky contact on InGaAs. A reduction of ϕ_b will reduce the LO power required to pump an InGaAs Schottky mixer [4], but it will also contribute to increase the nonlinear capacitance of the diode. This increase of the capacitance will lead to higher shunting effect at THz frequencies. Also, the higher the ϕ_b, the higher the tunnel current through the barrier, which will increase the ideality factor of the diode [3, 4].

Despite the possibility of optimizing the *In* fraction in a InGaAs semiconductor for a particular application [4], we have selected an *In* fraction of 0.53 since the resulting lattice constant matches InP subtrate, simplifying the fabrication technology of $In_{0.53}Ga_{0.47}As$ devices [3]. From now on, every time we speak of InGaAs we will be referring to $In_{0.53}Ga_{0.47}As$.

Figs. 1 and 2 show a comparison of measurements [10, 11] and Monte Carlo simulations of the low field electron mobility and the velocity-field curves of bulk InGaAs (doping concentration $1\text{x}10^{14}$ cm^{-3}). The mobility of GaAs is included for comparison. The higher mobility of InGaAs than GaAs -Fig. 1- will lead to Schottky diodes with lower dc series resistance. In addition, InGaAs shows larger velocity saturation than GaAs, see Fig. 2, improving the performance of the diode under high field conditions.

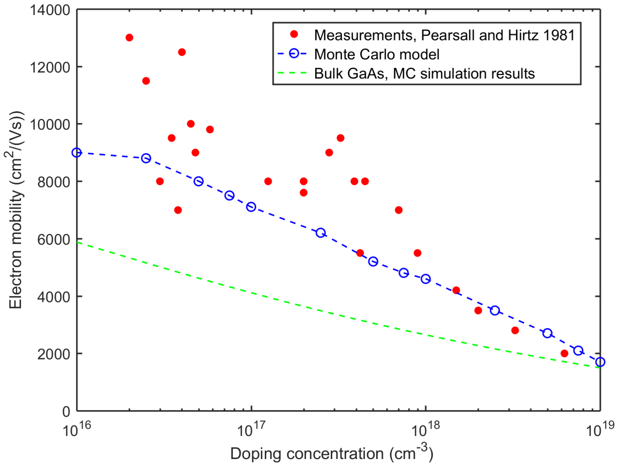

Fig. 1 Measurements [10] and MC simulations of the low field electron mobility of InGaAs as a function of the doping density.

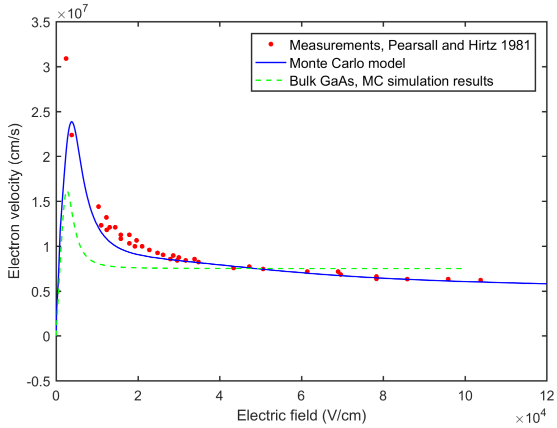

Fig. 2 Measurements [11] and MC simulations of velocity versus field curves for bulk InGaAs with doping concentration $1\text{x}10^{14}$ cm^{-3}.

III. ANALYSIS OF THZ INGAAS MIXERS

This section presents an analysis of the capabilities of InGaAs SHP mixers at THz frequencies in comparison with GaAs SHP mixers. The analysis is based on MCHB circuit simulations. The circuit impedances at the LO, RF and intermediate (IF) frequencies used in the simulations of the InGaAs mixers have been chosen to minimize the conversion loss at the LO power of minimum loss while for the GaAs mixers they have been set to the values provided in the literature. The evaluation of the equivalent input noise temperature of the mixers includes the contribution of the losses on the feed horn, filters and mixer waveguides, L_{rf}, as well as the resistive and mismatch losses in the IF matching circuit, L_{if}. Values of L_{rf} and L_{if} provided for GaAs Schottky mixers in the literature have been assumed in the simulations. In order to compare InGaAs and GaAs mixers, the diode parameters presented in the literature for GaAs mixer diodes have been also used for the InGaAs diodes. Table I shows the main circuit and diode parameters of the analyzed mixers.

TABLE I
DIODE AND CIRCUIT PARAMETERS OF THE SIMULATED INGAAS AND GAAS SHP MIXERS

	168 GHz SHP Mixer [12]		**360 GHz SHP mixer [13]**		**1.2 THz SHP mixer [1]**	
	GaAs	InGaAs	GaAs	InGaAs	GaAs	InGaAs
f_{RF} (GHz)	168		360		1230	
f_{LO} (GHz)	72		168		600	
V_{bias} (V)	0		0		0.5	0
Epi thick (nm)	75		85[a]		100[a]	
Epi doping (cm^{-3})	$2\text{x}10^{17}$		$2\text{x}10^{17}$		$5\text{x}10^{17}$ [a]	
Barrier height (eV)	0.89	0.21	0.85	0.21	0.8	0.21
Anode area (μm^2)	0.78		0.8		0.5	
$C_j(0)$ (*f*F)	1.28	2.57	1.3	2.6	1.21[a]	2.4
R_s (Ω)	21.4	13.6	18.0	12.4	20[a]	12.7
Z_{RF} (Ω)	60+j73	42+j36	83+j53	21+j21	27+j14[a]	4.5+j11.5
Z_{LO} (Ω)	95+j240	100+j75	147+j207	44+j37	38+j33[a]	7.5+j24
Z_{IF} (Ω)	100		100		50[a]	
L_{rf}, L_{if} (dB)	0.7, 1[a]		0.7, 1		0.7, 1.2[a]	

[a] Some data for the GaAs diodes are not available in the literature. In those cases, they have been optimized with MCHB or extrapolated from available data for similar mixers, see [9].

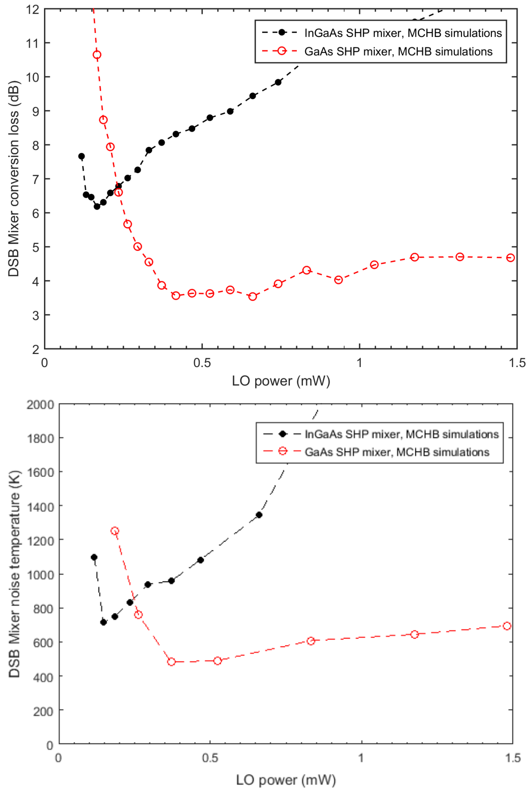

Fig. 3 DSB conversion loss and mixer noise temperature of the 168 GHz SHP mixer based on InGaAs and GaAs [12] diodes. Results obtained with MCHB.

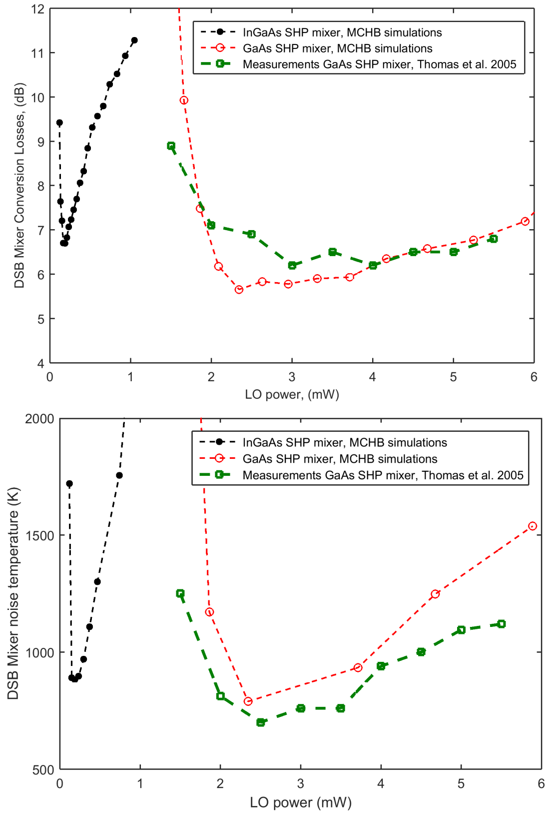

Fig. 4 DSB conversion loss and mixer noise temperature of the 360 GHz SHP mixers based on InGaAs and GaAs diodes, obtained with the MCHB tool. Measurements from [12] are also included.

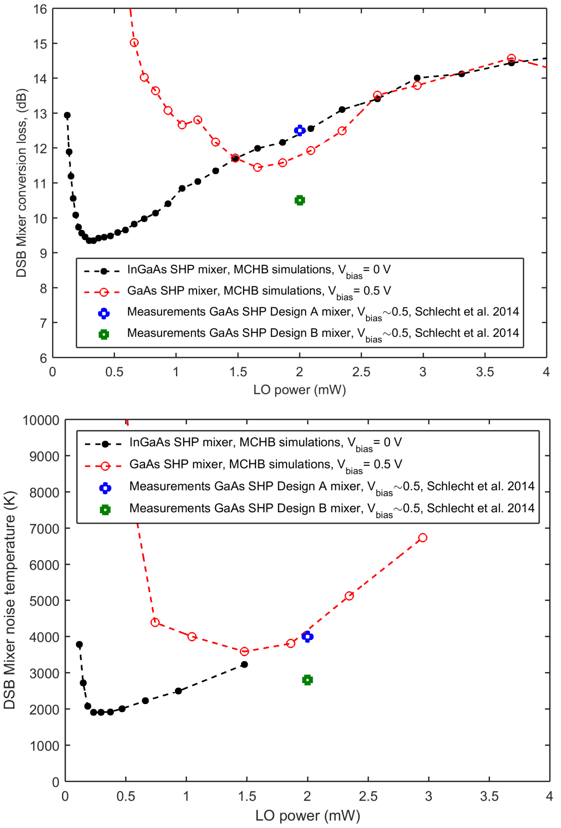

Fig. 5 DSB conversion loss and mixer noise temperature of the 1.2 THz SHP mixer based on InGaAs and GaAs SHP mixers obtained with MCHB. Measured results from [1] are included.

Figs. 3 to 5 show the mixer conversion loss and noise temperature for the InGaAs and GaAs SHP mixers described in Table I calculated with the MCHB tool. The most important conclusions from these figures are:

- The LO power to reach the minimum conversion loss and noise temperature of the InGaAs SHP mixers is around 1/4 of the corresponding GaAs SHP mixers because of the lower barrier height of the former.
- For the simulated mixers at frequencies below 1 THz, InGaAs mixers show higher conversion loss and noise temperature than the corresponding GaAs mixers because of the higher junction capacitance of the InGaAs diodes, which increases shunting effect (in this initial analysis, tunnel effect was not taken into account in the MC diode model).
- The GaAs 1.2 THz SHP mixer in [1] is biased in order to reduce the LO power requirements. According to simulations results in Fig. 5, an unbiased InGaAs 1.2 THz SHP mixer will require lower LO power than the biased GaAs mixer and it will provide better performance.

IV. FABRICATION AND TEST OF INGAAS DIODES

The MMTG is developing Schottky direct detectors and mixers based on InGaAs semiconductor at THz frequencies. Fig. 6 shows current versus voltage measurements of our InGaAs diodes with anode diameter 0.9 µm. Simulation results using physics based diode models including tunnel transport and barrier lowering due to image force are also included in the figures, showing a good agreement with the measured results.

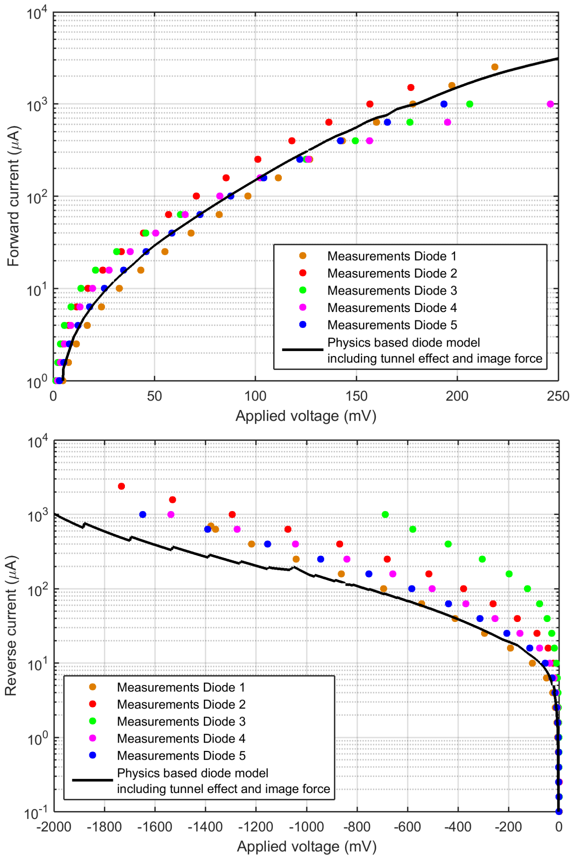

Fig. 6 Current versus voltage measurements under reverse and forwards conditions for InGaAs diodes of anode diameter 0.9 µm fabricated at the MMTG. Simulations results from physics based diode models are also presented.

V. Conclusion

A MCHB circuit simulator has been used to analyse the electrical and noise performances of InGaAs SHP Schottky mixers at the THz band. At frequencies below 1 THz, InGaAs mixers require LO powers around 1/4 of that required by GaAs mixers, but they show higher conversion loss and noise temperature. The use of InGaAs technology is expected to be very competitive at frequencies above 1 THz: while GaAs SHP mixers need to be biased, an InGaAs SHP mixer can operate without bias, requiring 1/4 of the LO power of the GaAs mixer and showing better performance.

Some initial fabrication results of InGaAs diodes at the MMTG have been presented, showing an excellent dc performance when compared with the expected performance provided by physics based diode models.

Acknowledgment

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