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Modeling of InAlAs/InGaAs/InAlAs DG-HEMT Mixer for Microwave Application

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Abstract : *This paper explores the potential of ultra-high frequency low noise InAlAs/InGaAs/InAlAs double gate high electron mobility transistor (DG-HEMT) for mixer applications. A comprehensive analytical approach is developed for InAlAs/InGaAs/InAlAs separate gate geometry DG-HEMT based mixer. Heterogeneous mixer configuration is employed in which both the signals, the local oscillator (LO) signal as well the radio frequency (RF) signal are applied at the same gate (gate 1). The dc offset is also applied at the other gate (gate 2) for better charge control. A mixer designed using InAlAs/InGaAs/InAlAs DG-HEMT is also found to perform better than a mixer based on conventional double gate-MOSFET in terms of conversion gain.*
Keywords - *Conversion gain, DG-HEMT, mixer, separate gate*

I. Introduction

Mixers perform a very crucial role of frequency translation in any practical communication system. Mixing of the LO and RF signals results in the generation of their sum and difference frequency components as up-converted and down-converted intermediate frequency (IF) signals [1-2]. Mixers have by far been realized using active non-linear devices such as MOSFET, MESFET, HEMT etc.[3-7] where the main task of these devices is to select and amplify the IF frequency and produce the desired signal at the output. In addition to this, the performance of a mixer is also judged by its ability to suppress/isolate spurs (spurious responses) and immunity against intermodulation distortion and other undesirable non-linear phenomena [8-9]. Various important performance parameters such as conversion gain, noise figure and third order intermodulation point are considered while designing a mixer [10].

This paper proposes an analytical model to study the performance of InAlAs/InGaAs/InAlAs separate gate DG-HEMT for mixer application. In the double heterostructure double-gate HEMT considered in the analysis, a gate electrode is placed on each side of the conducting channel. The mixing of the LO and RF signals applied at one of the gates generates intermediate frequency. A dc offset is applied to the second gate which renders better charge control, higher transconductance and better noise immunity. This overall, leads to a mixer which provides better isolation between the desired intermediate frequency signal and other spurious frequency components and better selectivity.

In this paper, the performance of double heterostructure DG-HEMT mixer is studied in terms of its output voltage frequency spectrum and conversion gain. InAlAs/InGaAs/InAlAs double heterostructure DG-HEMT based mixer is also found to exhibit better performance than the conventional DG-MOSFET based mixer.

II. Model Formulation

The schematic of separate gate InAlAs/InGaAs/InAlAs DG-HEMT [11-13] is shown in Fig.1. A symmetrical structure is assumed in which the doping profile, doping concentration, nature of the schottky-barrier and the dimensions of various layers in both the heterostructures is assumed to be same.

Fig. 2 shows a general block diagram of a mixer used at the receiving end of a communication system. A schematic circuit representation of the double heterostructure DG-HEMT proposed as a mixer is shown in Fig. 3. As illustrated in the figure, the local oscillator signal $v_{lo}(t)$ and radio frequency signal $v_{rf}(t)$ are applied to gate 1 and a constant dc bias is applied at the gate 2.

The resultant signal applied at gate 1 is therefore expressed as [14-17]

$$V_{gs1}(t) = v_{lo}(t) + v_{rf}(t) \tag{1}$$

Where

$$v_{lo}(t) = V_{LO} + v_{LO}\sin(2\pi f_{LO} t) \tag{2}$$

$$v_{rf}(t) = V_{RF} + v_{RF}\sin(2\pi f_{RF} t) \tag{3}$$

Where, V_{LO} and V_{RF} are the dc bias component of LO and RF signal respectively and v_{LO} and v_{RF} are maximum value of the ac component of LO and RF signal respectively.

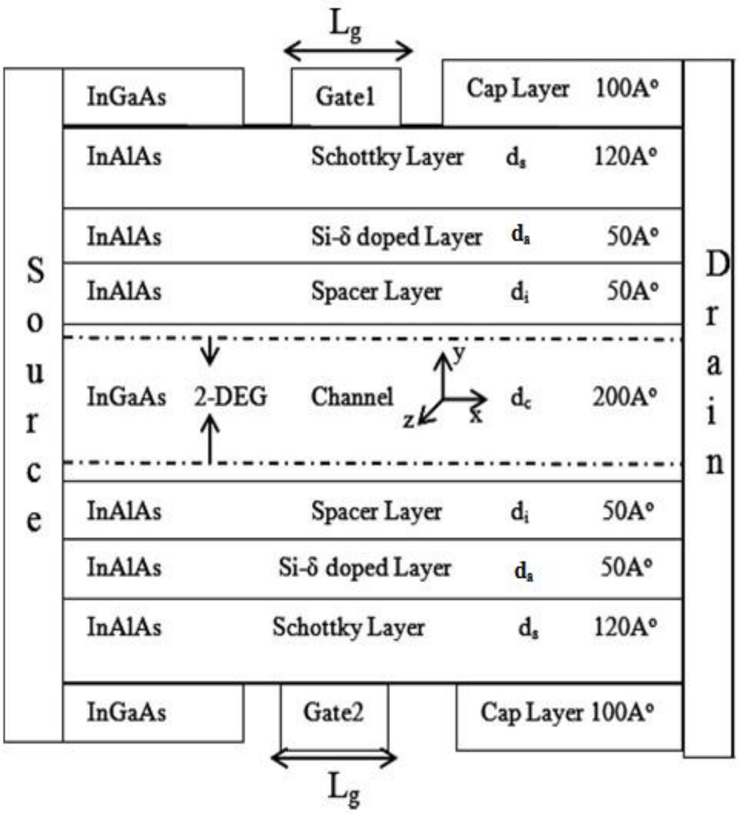

Fig. 1 Double-gate InAlAs/InGaAs/InAlAs structure HEMT [9-10]

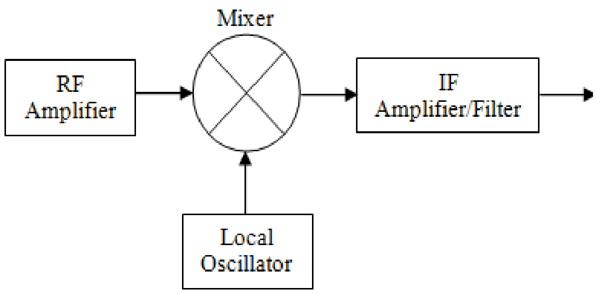

Fig. 2 Block diagram of mixer used in communication receiving system

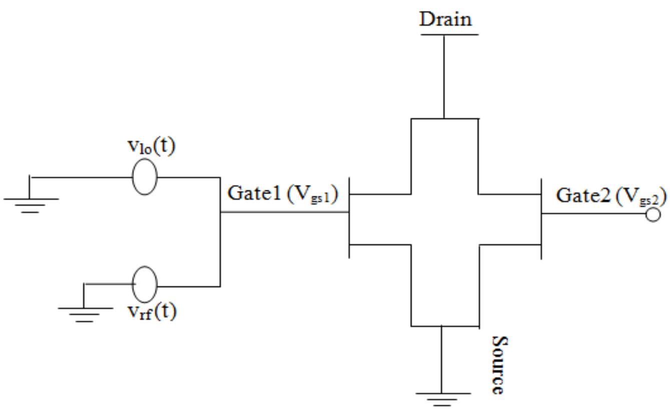

Fig.3. Schematic of proposed DG-HEMT mixer

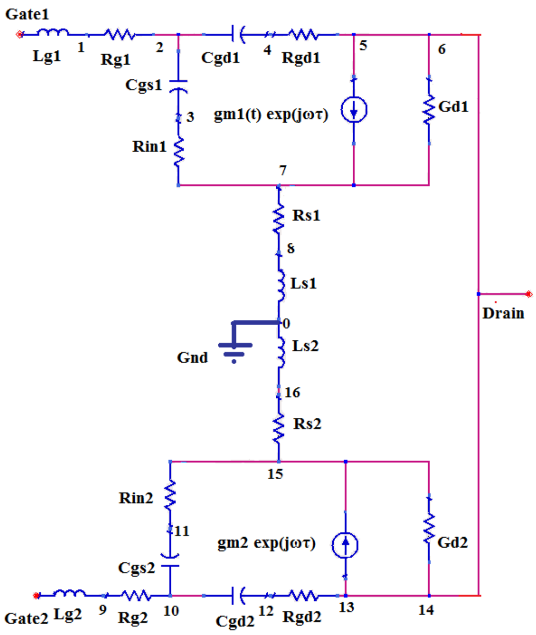

Fig. 4(a) Small signal equivalent circuit (SSEC) for DG-HEMT

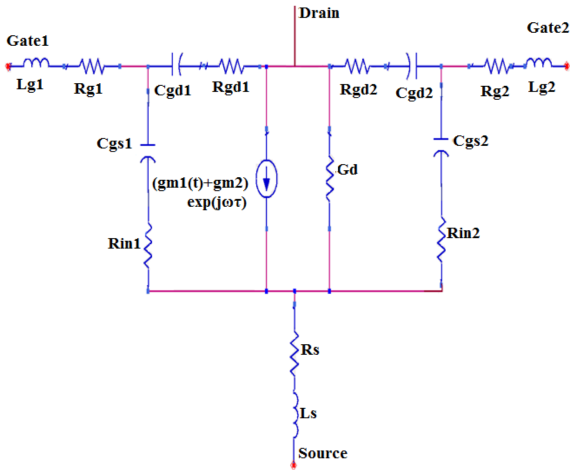

Fig. 4(b) Small signal equivalent circuit (SSEC) for DG-HEMT

Fig. 4(a) and Fig. 4(b) show the 3-port small signal equivalent (SSEC) circuit for the separate gate DG-HEMT illustrating the various small signal parameters such as transconductance ($g_{m1}(t)$, g_{m2}) between drain and two gates respectively, gate to source capacitances (C_{gs1}, C_{gs2}), gate to drain capacitances (C_{gd1}, C_{gd2}) and intrinsic resistances (R_{i1}, R_{i2}) etc. The voltage applied at both the gate electrode are different ($V_{gs1} \neq V_{gs2}$), therefore the equivalent circuit of separate gate DG-HEMT become three port circuit. As a result of this, the following assumptions can be made: $(gm1(t)+gm2)\exp(j\omega\tau)$ and $G_d = G_{d1}+G_{d2}$. Therefore, the resultant equivalent circuit is obtained as shown in Fig. 4(b) where, G_d is the output conductance, g_{m2} is the transconducatnce between gate2 and drain, and $g_{m1}(t)$ is the time varying transconductance between drain and gate1 of the DG-HEMT expressed as

$$gm_1(t) = \left.\frac{dI_{ds1}(t)}{dv_{lo}(t)}\right|_{\substack{V_{ds}=\text{constant} \\ V_{gs2}=\text{constant}}} \tag{4}$$

Where, $I_{ds1}(t)$ is the drain current due to LO signal applied at gate 1 evaluated as given in [11-12].

The mixing operation takes place in the device when large amplitude LO signal modulates the transconductance between drain and gate 1 of the device. When the RF signal is applied simultaneously at the same gate, the output signal produced at drain will be proportional to the amplitude and the frequency component of both the input signals i.e., LO as well as RF signal. The time varying transconductance is the main contributor to mixing due to which such a mixer is regarded as a transconductance mixer. In a double heterostructure DG- HEMT, a gate is placed on both sides of the conducting channel as shown in Fig.1. The buffer layer is replaced by another identical InAlAs/InGaAs heterointerface. Therefore, due to the removal of the buffer layer and elimination of the corresponding carrier injection into the buffer layer, drain to source capacitance (C_{ds}) does not form the part of the equivalent circuit of DG-HEMT [11-12]. The various extrinsic elements associated with the source inductance (L_s), source resistance (R_s), gate inductances (L_{g1} and L_{g2}) and gate resistances (R_{g1} and R_{g2}) of the device have been found to produce a negligible effect on the conversion gain and output of the mixer [2,18]. Therefore, an intrinsic equivalent circuit has been considered in which the various extrinsic element have not been included [11-12]. The mixing components generated due to the gate to source capacitance, gate to drain capacitance and intrinsic resistance are considered to be negligible [2]. Drain current generator (transconductance) was considered to be the main source of nonlinearity. The other circuit elements are assumed to be linear [18].

In the DG-HEMT mixer, the LO and RF signals are applied to the gate 1 and IF is extracted from the drain. The gate is usually biased near its turn on voltage and drain is biased in saturation region. The profile of transconductance with gate bias is the dominant factor in the frequency conversion processes. The nonlinear elements of the model are assumed to depend exclusively on gate voltage. Based on this assumption, small signal drain current due to the signal at gate 1 [2] is given as:

$$i_{ds1}(t) = g_{m1}(t)\ v_{rf}(t) \qquad (5)$$

The small signal drain current component $i_{ds1}(t)$ given in eq.(4) results in the mixing of the LO and RF signals obtained at the output of the mixer, and drain to source current due to a fixed bias applied at the gate 2 is given by I_{ds2} [11-12].

The total drain to source current $I_{dsT}(t)$ for double heterostructure double gate HEMT mixer is obtained as the sum of components produced due to LO and RF signals applied at gate 1 and the fixed dc bias which is applied at the other gate 2 [9-10,19]. Thus, the output voltage of InAlAs/InGaAs/InAlAs DG-HEMT mixer is expressed in term of $I_{dsT}(t)$ and the load resistance (R_L=50 Ω) as:

$$V_{out} = I_{dsT}(t)\, R_L \qquad (6)$$

III. Results And Discussion

Fig. 5(a) and Fig. 5(b) shows the time-domain output of the separate gate geometry DG-HEMT mixer obtained analytically for different values of v_{LO} when V_{ds} = 1 V, V_{gs2} = 0 V, V_{LO} = 0.4 V, V_{RF} = 0.5 V and v_{RF} = 0.02 V. A modulated output voltage is observed resulting due to mixing of the LO signal with frequency f_{LO}= 0.9 GHz and RF signal with frequency f_{RF}= 1 GHz which results in the generation of two intermediate frequencies; up-converted IF and down-converted IF. It is observed from the Fig. 5(a) and Fig. 5(b), that the degree of modulation changes with the magnitude of the local oscillator signal v_{LO}. 100% modulation takes place when v_{LO} is same as v_{RF}, indicating that all the information present at input is transferred to the output of the mixer.

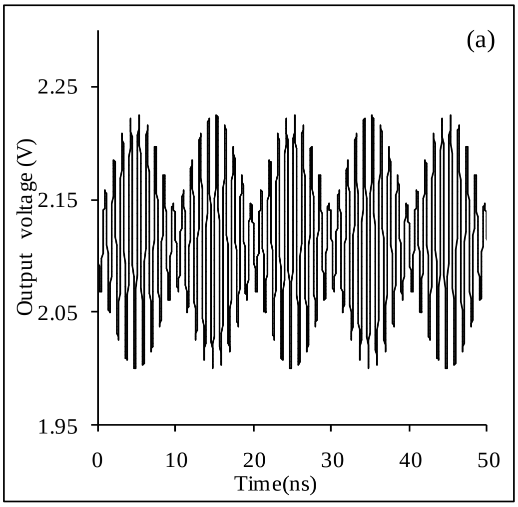

Fig. 5(a) Variation of output voltage with time when v_{LO} = 0.05 V, V_{ds}= 1 V, V_{gs2}= 0 V.

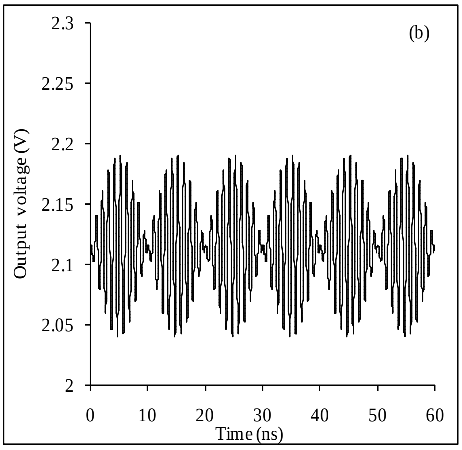

Fig. 5(b) Variation of output voltage with time when v_{LO} = 0.02 V; V_{ds}= 1 V, V_{gs2}= 0 V.

Fig. 6(a) shows the frequency spectrum of the DG-HEMT mixer output. The major frequency components observed include the LO frequency (f_{LO}= 0.9 GHz), RF (f_{RF}= 1 GHz) and intermediate frequencies, up converted IF $f_{LO}+f_{RF}$ at 1.9 GHz and down converted IF $f_{LO}-f_{RF}$ at 0.1 GHz. Some additional spurious frequency components are also observed at 0.8 GHz with amplitude of 1 mV and 1.8 GHz with amplitude of 9 mV due to nonlinearity of the device. The mixer performance can be improved by subsequent, better amplification at the desired IF frequency and filtering out of the undesired frequency components.

Fig. 6(b) shows the frequency spectrum of the mixer output when the amplitudes of LO and RF signals, i.e., v_{LO} and v_{RF} are the same. A degraded mixer performance is observed in terms of greater amplitude of spurious frequency component at frequency of 1.8 GHz. In addition to this, the DG-HEMT amplifier should exhibit good selectivity and high gain at the IF.

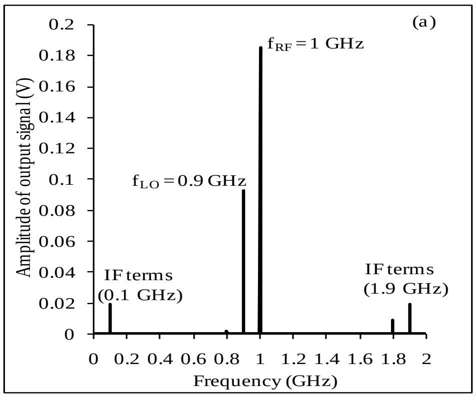

Fig. 6(a) Frequency spectrum of DG-HEMT as mixer

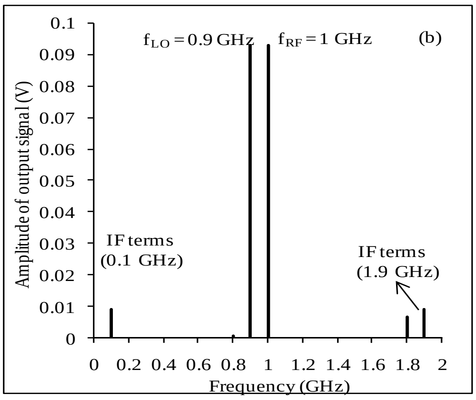

Fig. 6(b) Frequency spectrum of DG-HEMT as mixer application when V_{gs2} = -0.1 V

Fig. 7 shows the variation of conversion gain with LO dc bias; when f_{LO}= 0.9 GHz, f_{RF}= 1 GHz, v_{LO}= 0.04 V, V_{RF} = 0.5 V, v_{RF} = 0.02 V, V_{ds} = 1 V and V_{gs2} = 0 V. It is one of the most important performance parameter of the mixer. It indicates the relative level of an output which has been converted to a frequency and differs from that of the input. From the figure, maximum conversion gain of -16.2 dB for down-converted frequency (0.1 GHz) is observed for 100 nm gate-length DG-HEMT based mixer at LO dc bias (V_{LO}) = 0.9 V. The Fig. 7(inset), shows conversion gain of -46 dB for f_{LO}= 0.9 GHz and f_{RF}= 1 GHz for a 100 nm gate-length double gate MOSFET RF mixer [14]. The proposed, DG-HEMT mixer model exhibits better performance than mixer based on conventional DG-MOSFET.

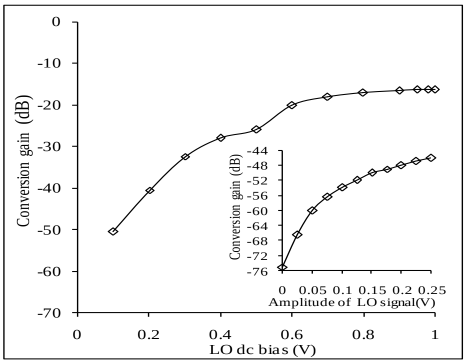

Fig. 7 Variation of conversion gain vs. LO dc bias for DG-HEMT, (Inset) variation of Conversion Gain vs. LO dc bias for double gate MOSFET RF mixer [15]

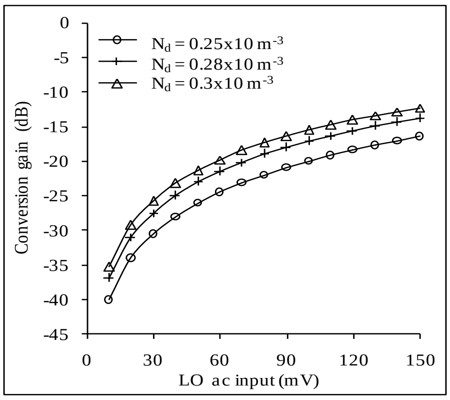

Fig. 8 Variation of conversion gain with LO ac input (v_{LO}) for different value of donor layer doping concentration (N_d)

Fig. 8 shows the variation of conversion gain obtained for the down-converted frequency (0.1 GHz) with LO ac input (v_{LO}) for different values of donor layer doping concentration (N_d); when f_{LO} = 0.9 GHz, f_{RF} = 1 GHz, V_{LO} = 0.4 V, V_{RF} = 0.5 V, v_{RF} = 0.02 V, V_{ds} = 1 V and V_{gs2} = 0V. It can be observed that as the value of donor layer doping concentration is increased, conversion gain also increases due to an increase in drain to source current.

Fig. 9 illustrates the effect of dc gate bias at gate2 on the output power of the mixer. It is evident from the figure, as the value of dc gate bias is decreased, the output power also decreases. This implies that the, output of the mixer can be controlled by the dc bias applied at other gate (gate2).This shows better controllability of the performance achieved in the separate gate DG-HEMT mixer due to the presence of the two gates.

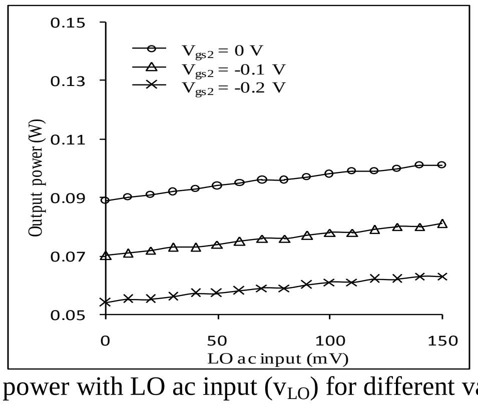

Fig.9 Variation of output power with LO ac input (v_{LO}) for different value of dc gate bias (V_{gs2})

IV. Conclusion

A systematic study of InAlAs/InGaAs/InAlAs separate gate DG-HEMT for application as a mixer is presented in this paper. Heterogeneous configuration is employed where the RF signal and LO signal are applied at the gate1and a fixed bias (V_{gs2}) is applied at the gate 2. An analytical approach is proposed to study the performance of InAlAs/InGaAs/InAlAs DG-HEMT mixer in terms of its output voltage, transconductance, conversion gain, and output power. Further, from the frequency spectrum, when the amplitude of V_{LO} and $V_{RF}$is same, it is observed that the performance of mixer degrades with the generation of higher amplitude spurious signal at 1.8 GHz frequency. Conversion gain obtained analytically for double heterostructure DG-HEMT mixer is compared with that of double gate MOSFET RF mixer. It is found that DG-HEMT mixer gives better conversion gain as compared with double gate MOSFET RF mixer.

Acknowledgements

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