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Improved modeling on the RF behavior of InAs/AlSb HEMTs

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The leakage current and the impact ionization effect causes a drawback for the performance of InAs/AlSb HEMTs due to the InAs channel with a very narrow band gap of 0.35 eV. In this paper, the conventional HEMT small-signal model was enhanced to characterize the RF behavior for InAs/AlSb HEMTs. The additional gate leakage current induced by the impact ionization was modeled by adding two resistances R_{Gh1} and R_{Gh2} shunting the C_{gs}–R_i and C_{gd}–R_j branches, respectively, and the ionized-drain current was characterized by an additional resistance R_{mi} parallel with the output resistance R_{ds}, meanwhile the influence of the impact ionization on the transconductance was modeled by an additional current source g_{mi} controlled by V_{gs}. The additional inductance, evaluated as a function of $f(\omega,R)$, was introduced to characterize the frequency dependency of impact ionization by using the impact ionization effective rate $1/\tau_i$ and a new frequency response rate factor n, which guaranteed the enhanced model reliable for a wide frequency range. As a result, the enhanced model achieved good agreement with the measurements of the S-parameters and Y-parameters for a wide frequency range, moreover, the simulated results of the stability factor K, the cutoff frequency f_T, the maximum frequency of oscillation f_{max}, and the unilateral Mason's gain U were estimated to approach the experimental results with a high degree.

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1. Introduction

Compared with the conventional InAlAs/InGaAs/InP HEMTs, the InAs/AlSb HEMT exhibits high electron mobility and high peak velocity, making it advantageous for high-frequency and low power-dissipation applications, as well as for very low input-signal amplification [1–4], for example, it is potential to be the device for next generation of low noise amplifier used in the receiver of deep-space exploration [5].

However, compared with other HEMTs, the impact ionization effect becomes more important issue for InAs/AlSb HEMTs as the drain bias increases because the InAs channel has a very narrow band gap of 0.35 eV. The impact ionization results in serious leakage current, additional ionized-drain current, and the enhanced trans-conductance. The impact ionization effect shows frequency dependency, it performs at low frequency, and could not be ignored until a dozen of gigahertz, which makes the device's S-parameters, Y-parameters, the stability factor K and Mason's Gain U exhibit abnormal behaviors at low frequency [6,7,9]. In this case, an improved small-signal model (SSM) to characterize such special RF performances of InAs/AlSb HEMT is required essentially, which is important for the further circuit design.

However, as we know, there are very few reports specially focused on the small-signal equivalent circuit (SSEC) model for the impact ionization effect on InAs/AlSb HEMT. A SSEC model of the InAs/AlSb HEMTs was recently reported in Ref. [9], it was extended on the base of the conventional HEMT model in [13] to characterize the Schottky electrons gate leakage current by introducing the additional R_{gs} and R_{gd} shunting C_{gs} and C_{gd}, respectively, however, the influence of the impact ionization effect to the gate leakage current and drain current was not taken into account. In Ref. [7], the structure of the LR-series parallel with R_{ds} was too simple to accurately model the impact ionization effect, and in Ref. [21], the combination of the voltage controlling current source g_m and C_m-R_m series used to model the impact ionization was semi-physical. For further improvement, a new enhanced SSEC model is proposed in this paper, which allowed a significant characterization and prediction for the RF behavior of InAs/AlSb HEMTs over a wide frequency range. The comparison of the modeled results with the experimental data showed the reliability of the proposed model.

2. Physical analysis

The currently popular epitaxial structure for InAs/AlSb HEMT is shown in Fig. 1. The two-dimension electron gas (2-DEG) is generated in the InAs channel on the side of InAs/AlSb heterostructure.

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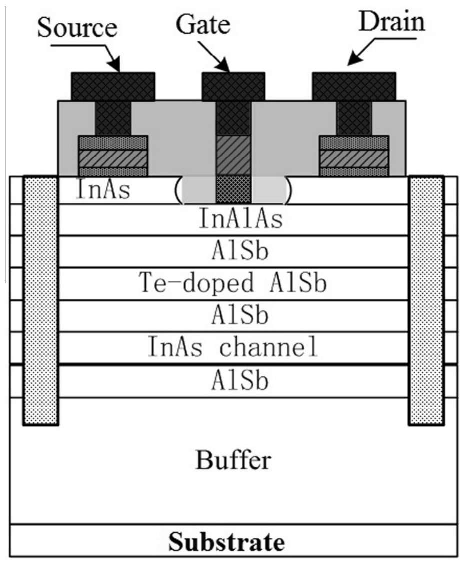

Fig. 1. Epitaxial structure of InAs/AlSb HEMT [5,9].

The density of 2-DEG is determined by the Schottky barrier under the gate-electrode, which is controlled by the gate bias. However because the InAs material has a very narrow band-gap of 0.35 eV and the InAs/AlSb heterostructure possesses type-II staggered energy-band diagram alignment, the device suffers from critical gate leakage current. First, the electrons tunneling through the AlSb Schottky-barrier leave the device through the gate contact to generate the Schottky gate leakage current I_{Ge} [21], which is sensitive with the AlSb Schottky barrier height [10]. On the other hand, as the drain bias increases, the carriers in the InAs channel obtain enough energy to impact with the lattice atoms in the high field between drain and gate to induce superfluous electron–hole pairs, the generated holes travel across the small valence band barrier between the gate and the channel to contribute an additional gate leakage current I_{Gh}, which could be characterized by the bell-shape in the curve of the gate leakage current as the function of gate bias [3,4]. In addition to the influence to the gate leakage current, the impact ionization affects the drain current as well. The ionized holes are accumulated in the gate–drain region of the buffer to generate a positive space charge, leading to an enhanced electron density under the gate electrode on the drain side of the channel and resulting in a further opened channel, which makes the drain current enhanced and exhibit an unsaturated behavior with the increasing drain bias, as Kink effect [11,12]. A positive feedback makes the impact ionization seriously [6]: The redundant holes not leaving the device though the gate are transferred across the protect layer and accumulated in the source–gate region of the InAs channel and the AlSb buffer layer, hence a positive charge space is formed to attract more ionized electrons generated in the high-field, which makes more holes generated.

The impact ionization effect shows frequency dependency, it performs obviously at the low frequency and usually dissolves gradually as the frequency increases to a dozen of gigahertz for InAs/AlSb HEMTs [6,7,15]. Therefore, the impact ionization effect should be taken into account when the device is applied from S band to Ku band.

3. Small-signal equivalent circuit model

On the base of the conventional SSEC model of HEMTs [13], the improved SSEC model to characterize the RF behavior of the InAs/AlSb HEMTs considering the impact ionization effect is proposed as shown in Fig. 2

3.1. Gate leakage current characterization

Due to the different mechanism, the modeling of the Schottky gate current I_{Ge} and the holes gate current I_{Gh} are taken into account, respectively. As shown in Fig. 2, two additional resistances R_{Ge1} and R_{Ge2} shunting $C_{gs} - R_i$ and $C_{gd} - R_j$, respectively, are introduced to provide the accesses of I_{Ge} [14]. Because I_{Ge} is not sensitive with frequency, R_{Ge1} and R_{Ge2} are considered as constants. The other couple of resistances R_{Gh1} and R_{Gh2} are introduced to model the extra equivalent path for I_{Gh}. Because I_{Gh} is attributed to the impact ionization effect, thus I_{Gh} performs frequency dependency, therefore two moderating inductances L_{Gh1} and L_{Gh2} in series with R_{Gh1} and R_{Gh2}, respectively, are introduced to characterize the frequency dependency of I_{Gh} by adjusting the phase of the impedance

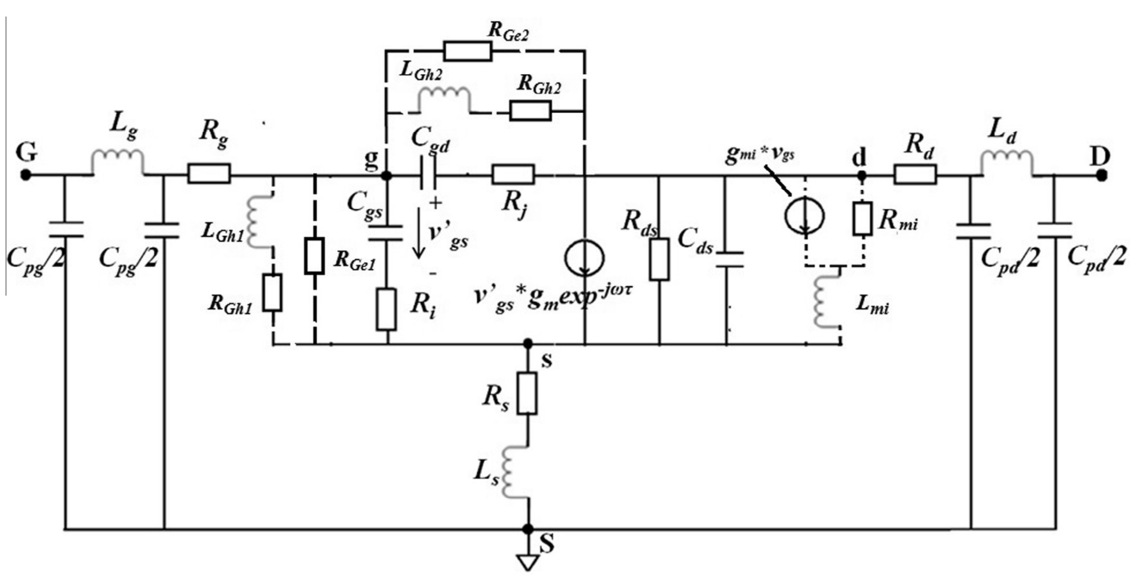

Fig. 2. Enhanced small-signal equivalent circuit for the InAs/AlSb HEMT. The components with solid line present the conventional HEMTs modeling part. The components with dash line are introduced to model the leakage current. The components with dot line are introduced to model the ionized-drain current.

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