An optimized fitting function with least square approximation in InAs/AlSb HFET small-signal model for characterizing the frequency dependency of impact ionization effect

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An enhanced small-signal model is introduced to model the influence of the impact ionization effect on the performance of InAs/AlSb HFET, in which an optimized fitting function $D(\omega\tau_i)$ in the form of least square approximation is proposed in order to further enhance the accuracy in modeling the frequency dependency of the impact ionization effect. The enhanced model with $D(\omega\tau_i)$ can accurately characterize the key S parameters of InAs/AlSb HFET in a wide frequency range with a very low error function EF. It is demonstrated that the new fitting function $D(\omega\tau_i)$ is helpful in further improving the modeling accuracy degree.

Keywords: InAs/AlSb HFET, impact ionization, frequency dependency, small-signal equivalent circuit model

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1. Introduction

The InAs/AlSb hererojunction field-effect transistor (HFET) is receiving attention as a promising candidate of next-generation devices for high-frequency, high-speed, and low-dissipation applications because of its high electron mobility and peak velocity of the carriers, especially at cryogenic temperature.[1,2] However, the very narrow band gap of the InAs channel (0.35 eV) results in the impact ionization effect easily happening and causes the performance of the device to degrade. At higher drain bias, the carriers with enough energy impact with lattice atoms to generate a lot of electron–hole pairs, and the generated holes can transmit from channel to gate electrode to form a leakage current access because of the lack of an effective hole barrier in the InAs/AlSb HEMT structure, leading to an enhanced gate-leakage current of InAs/AlSb HFET which could be observed.[3,4] On the other hand, the ionized holes accumulated in the gate-drain region of the buffer form a positive space charge region, which causes the channel to further open and thus enhances the drain current.[5,6] When a small signal with radio frequency is input, the influence of the impact ionization effect on the device's RF performance shows strong frequency dependency.[7,8] This influence occurs at low frequency, whereas it becomes insignificant as the frequency increases continually, and cannot be observed up to several gigahertz.[7,8] Therefore, the modeling of the frequency dependency of impact ionization is necessary to investigate InAs/AlSb HFET technology, and is important for further circuit design. In Ref. [9], we proposed a model with a fitting function of $1+\mathrm{j}(\omega\tau_i)^n$ to characterize the frequency dependency of the impact ionization effect, but without a very high accuracy degree. Therefore, in this paper, we propose an enhanced model with fitting function $D(\omega\tau_i)$ in the form of the least square method in order to further enhance the accuracy of the small-signal model for characterizing the influence of frequency dependency of impact ionization on the RF performance of InAs/AlSb HFET.

2. Small-signal modeling

On the basis of our small-signal model (SSM) in Ref. [9], a further enhanced SSM is proposed, focusing on the frequency dependency of the impact ionization effect by introducing a new least square fitting function $D(\omega\tau_i)$, its equivalent circuit is shown in Fig. 1.

Two voltage controlling current sources g_{m1} and g_{m2}, regulated by v_{gs} and v_{dg} respectively, are introduced to model the gate-leakage current I_G as a function of gate bias and drain bias. Actually, the gate-leakage current I_G is composed of the Schottky leakage current I_{Ge}, and the hole leakage current I_{Gh}, according to Eqs. (1)–(3), and given by

$$I_G = I_{Ge} + I_{Gh}, \tag{1}$$

$$I_{Ge} = SA^*T^2 \exp\left(-\frac{q\phi_B}{kT}\right)\left[\exp\left(\frac{-q\Delta V}{nkT}\right)-1\right], \tag{2}$$

$$I_{Gh} = I_D\chi(E)L_{eff}(E)T_h(E), \tag{3}$$

where $\chi(E)$ is the ionization rate per unit length (impact ionization coefficient), $L_{eff}(E)$ is the effective length of the high-field domain, and $T_h(E)$ is the tunneling probability.[10] The expression of I_{Ge} is obtained from the hot electron emission model,[11] S is the area of gate electrode, A^* is the effective

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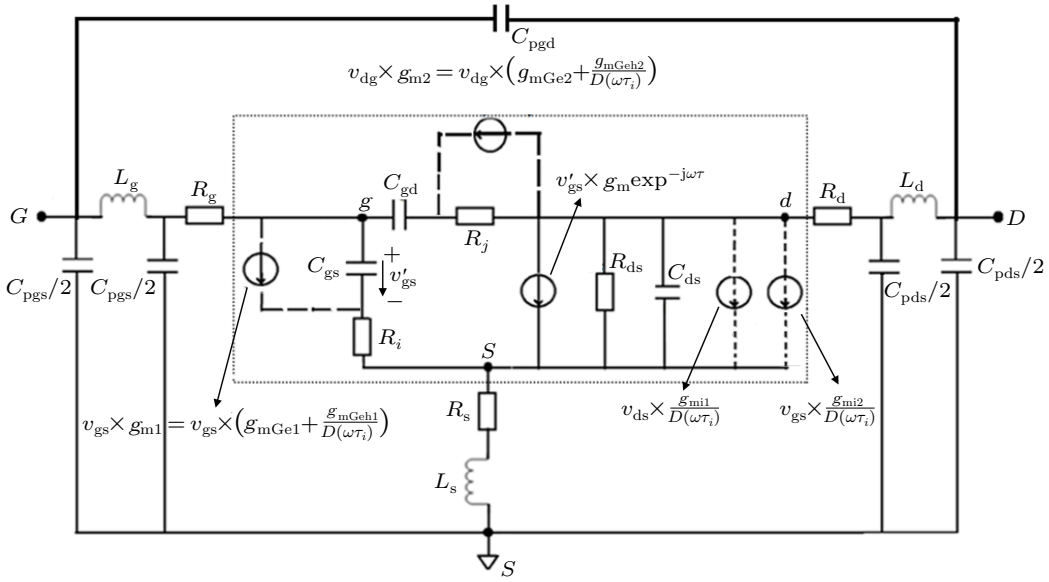


Fig. 1. Small-signal equivalent circuit for the InAs/AlSb HFET. The part in the dotted line square frame shows the intrinsic parameters, and the part outside the frame presents the extrinsic parameters.

Richardson constant, ΔV is the voltage across the barrier, n is the ideal factor, T is the thermodynamic temperature, e is the electron charge, k is the Boltzmann constant, and $\phi_{\rm B}$ is the Schottky barrier height.

The $I_{\rm Ge}$ is induced by the electrons transferring across the Schottky barrier, and it is not sensitive to frequency, thus $I_{\rm Ge}$ is modeled by two constants $g_{\rm mGe1}$ and $g_{\rm mGe2}$. On the other hand, $I_{\rm Gh}$ is induced by the impact ionization effect, and it is modeled by $g_{\rm mGh1}$ and $g_{\rm mhG2}$. Because the impact ionization effect takes effect mainly at a low frequency and it can be neglected as frequency increases, hence the influence of the modeling components on $I_{\rm Gh}$ also follows the frequency dependency, which could be characterized by a function $D(\omega\tau_i)$. Constant $1/\tau_i$ infers the happening rate of impact ionization, which decreases dramatically at the ultra-low drain bias without impact ionization, and it also suggests the transit time of holes from the impact generation to accumulation into positive field.[4,8] Therefore, the two current sources $g_{\rm m1}$ and $g_{\rm m2}$ for modeling the gate-leakage current are expressed as

$$g_{\rm m1}=g_{\rm mGe1}+\frac{g_{\rm mGh1}}{D(\omega\tau_i)}, \tag{4}$$

$$g_{\rm m2}=g_{\rm mGe2}+\frac{g_{\rm mGh2}}{D(\omega\tau_i)}. \tag{5}$$

The influence of the impact ionization effect on the drain current $I_{\rm D}$ can be modeled by two voltage controlling current sources $g_{\rm mi1}$ and $g_{\rm mi2}$. The $g_{\rm mi1}$ is controlled by the drain-gate voltage $v_{\rm ds}$ in order to suggest the influence of the drain bias on $I_{\rm D}$; the other source featured by $g_{\rm mi2}$ is controlled by $v_{\rm gs}$ to moderate the drain current further, and also to facilitate the exhibition of the varied trans-conductance induced by the impact ionization effect. In the same way as that for treating $g_{\rm mGh1}$ and $g_{\rm mGh2}$, $g_{\rm mi1}$ and $g_{\rm mi2}$ are also modified by $D(\omega\tau_i)$ in order to present the frequency dependency, which moderates the magnitude and the phase of the output resistance, and makes the output exhibit inductive performance at a low frequency.

Because the device performance influenced by impact ionization at the varied frequency points can be considered as a collection of discrete data, we propose to take $D(\omega\tau_i)$ to be the form of best square approximation, with its least mean square error, in order to make the modeled results approach the measurements in a high degree. The expression of $D(\omega\tau_i)$ is given as follows:

$$D(\omega\tau_i)=\left(1+\sum_{i=1}^{m}a_i(\omega\tau_i)^i\right)+j\left(\sum_{i=1}^{m}b_i(\omega\tau_i)^i\right), \tag{6}$$

where m is the dimension of the fitting function, $[a_i]$ is the real part fitting matrix, and $[b_i]$ is the imaginary part fitting matrix. At the frequency of 0 Hz, $D(\omega\tau_i)$ is equal to 1, making $g_{\rm m1}$ the sum of $g_{\rm mGe1}$ and $g_{\rm mGh1}$, and $g_{\rm m2}$ the sum of $g_{\rm mGe2}$ and $g_{\rm mGh2}$; as frequency increases, the absolute value of $D(\omega\tau_i)$ increases; when the frequency approaches several gigahertz, $D(\omega\tau_i)$ makes impact ionization ignored by cutting off the current access.

3. Verification

In this paper, the AlSb/InAs HFET experimental data extracted from Ref. [4] are referred for evaluating our new fitting function $D(\omega\tau_i)$. It was said in Ref. [4] that the bias condition of $V_{\rm GS}=-1$ V and $V_{\rm DS}=0.6$–1 V has been proved with impact ionization. The extrinsic parameter values of SSM at this bias voltage in Ref. [4] are directly used in our model. In order to simplify our extraction procedure of intrinsic parameters, the dimension of the fitting function m is initially taken to be 1, and the values of a_1 and b_1 are determined as 0 and 1, respectively. In this case, the optimal values of the intrinsic pa-

rameters can be extracted directly with the method in Ref. [9], as shown in Table 1.

Table 1. Values of extracted intrinsic parameters.

Parameter	$V_{GS} = -1.0$ V		
	$V_{DS} = 0.6$ V	$V_{DS} = 0.8$ V	$V_{DS} = 1.0$ V
C_{gs}/fF	108	117.7	143.1
C_{ds}/fF	15.4	15	24.2
C_{gd}/fF	26.2	25.5	14.8
g_m/mS	47.2	55	65.4
R_i/Ω	10	7.6	7.9
R_j/Ω	20.5	30	41.8
R_{ds}/Ω	159	162.1	183.9
τ/ps	0.2	0.4	0.38
$-g_{mGe1}$/mS	0.395	1.486	3.021
$-g_{mGh1}$/mS	2.528	6.035	11.236
g_{mGe2}/mS	0.804	2.548	4.975
g_{mGh2}/mS	1.395	3.676	4.019
g_{mi1}/mS	22.1	23.2	15.9
g_{mi2}/mS	20	30.3	30
τ_i/ps	82	54	38

Next, the influence of $D(\omega\tau_i)$ with different-dimension value m can be achieved by tuning $[a_i]$ and $[b_i]$ with different values. The error function (EF) between the modeled result and measurement for S parameters is obtained as

$$\mathrm{EF} = \frac{1}{4N}\sum_{j=1}^{2}\sum_{i=1}^{2}\left(W_{ij}\sum_{p=1}^{N}\left(S_{ij}^{\mathrm{m}}(p) - S_{ij}^{\mathrm{e}}(p)\right)^2\right), \qquad (7)$$

where N is the number of the samples at different frequencies, p is the responding frequency index of the sample, S_{ij}^{m} and S_{ij}^{e} are the modeled and experimental S parameters, respectively, and W_{ij} is the weight factor to describe the optimized priority for S_{ij}. In this case, in order to emphasise S_{22}, providing the most direct view of the impact ionization,[10] W_{22} is set to be 2, whereas W_{11}, W_{12}, and W_{21} are all set to be 1.

At the bias of $V_{GS} = -1$ V and $V_{DS} = 1$ V, EF as a function of N and m for S parameters by dB unit is shown in Fig. 2, it is easily found that EF decreases with increasing sample number N and fitting function dimension m. When m is higher than 3, its continual increasing makes little enhancement of EF, but can strongly increase the simulation complexity and calculation time. Therefore, $m = 3$ can be considered as an appropriate value. Table 2 gives the comparison among EF results with different m values (ranging from 1 to 3 when $N = 500$), and for the case of $m = 3$ the lowest EF value of 0.84 is achieved.

Table 2. EF values with different m values when n is 500.

	$m=1$	$m=2$	$m=3$
EF	3.75	1.21	0.84

The experimental result of the InAs/AlSb HFETs fabricated in Ref. [4] under the bias condition of $V_{GS} = -1$ V and $V_{DS} = 0.6$–1 V is referred in this paper to evaluate the accuracy of our enhanced model. The S parameters for 0.05–40.5 GHz are modeled. Figures 3 and 4 show the comparisons of the key S-parameter between the simulation results from the model with $m = 3$ and the measurements. The S_{11} and S_{22} are the input and output reflection coefficient, respectively, and S_{21} can be considered as the output gain of the device. It is found that the simulation result from the SSM with the fitting function $D(\omega\tau_i)$ achieves good agreement with the measurement.

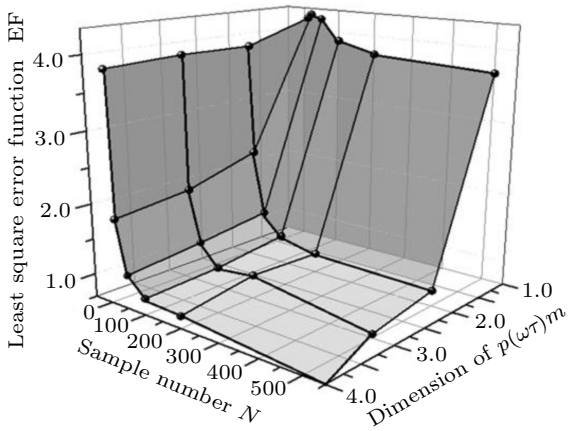


Fig. 2. Least square error function EF versus sample number N and the fitting function dimension m for S parameter simulation for 0.5–40.5 GHz.

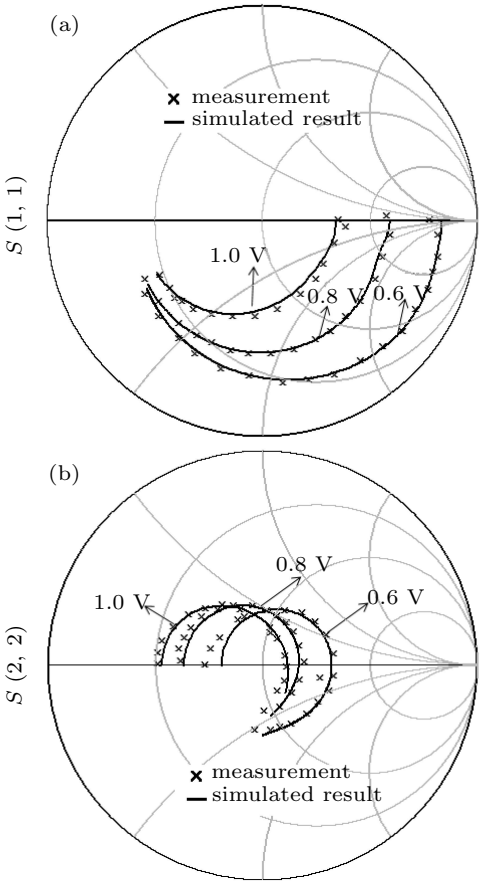


Fig. 3. Simulation results of (a) input reflection coefficient S_{11} and (b) output reflection coefficient for S_{22} in a frequency range of 0.05–40.5 GHz.

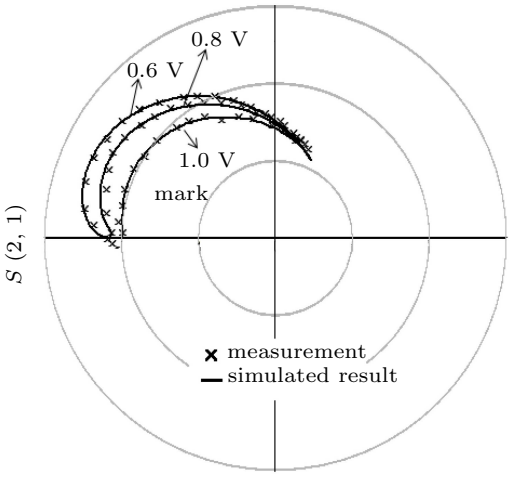


Fig. 4. Output gain S_{21} simulation result in a frequency range of 0.05–40.5 GHz.

4. Conclusions

An enhanced small-signal equivalent circuit model of InAs/AlSb HEFT, focusing on the impact ionization effect, is proposed. Two couples of voltage controlling current sources g_{mGh1}–g_{mGh2} and g_{mi1}–g_{mi2} are introduced to model the influences of the impact ionization effect on the gate-leakage current and the ionized-drain current, respectively. An optimized fitting function $D(\omega\tau_i)$ in the form of least square approximation is proposed in order to further enhance the accuracy in modeling the frequency dependency of the impact ionization effect. It is found that the improved model with $D(\omega\tau_i)$ can accurately characterize the key S parameters of InAs/AlSb HEFT in a wide frequency range, and a much lower error function EF can be achieved with $m = 3$. It is demonstrated that the new fitting function $D(\omega\tau_i)$ is helpful in further improving the modeling accuracy degree.

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