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# Characterization and Modeling of Microwave Noise in InP/InGaAs Composite Channel High Electron Mobility Transistors (HEMTs)

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## I. Introduction

InP-based high electron mobility transistors (HEMTs) have demonstrated their technological advantages for high-speed and high frequency application. During the past several years, significant improvements have been presented for high frequency and noise performance of HEMTs. At present, InP-based HEMTs show the highest cut-off frequencies and the lowest noise of all three terminal semiconductor devices. Moreover, to further improve the device performance, InP-based HEMTs with an InGaAs/InP composite channel were proposed and fabricated [1]. It has been demonstrated that, by using the InGaAs/InP composite channel structure, the device breakdown voltage, frequency performance and output power could be remarkably improved due to the suppression of electron impact ionization and better electron transport properties at high electric field in InP. Recent works on the composite channel HEMT have been focused on the channel design to improve the power performance [2,3,4]. However, little attention has been paid on the microwave noise characteristics of InP HEMTs with composite channel even though InP HEMTs are considered to be one of the most important devices at high frequency.

In this work, the study of the microwave noise performance for InGaAs/InP composite channel HEMT compared to InGaAs channel is performed. Detailed microwave noise characteristics of InP-based HEMT are presented. An interesting result is that the minimum noise figure ($NF_{min}$) decreases at the higher bias point for the composite channel device. This result is different from the single channel device that the minimum noise figure increases with the increase of the bias. An analytical model was provided to study the channel noise for both devices and verify the influence of the different channel structure on the noise performance.

## II. Experiment

The InP-based HEMTs used in this work were grown by molecular beam epitaxy on semi-insulating InP substrate. The composite channel is consisting of $In_{0.53}Ga_{0.47}As$ channel and undoped InP channel and doped InP. For the referenced single InGaAs channel device, an $In_{0.6}Ga_{0.4}As$ channel was used. The gate lengths of the devices with InGaAs/InP composite channel and InGaAs single channel used for tests are 0.4 and 0.25 μm, respectively.

## III. Results and Discussion

The noise performance was characterized by using an ATN load-pull system. Fig.1 shows $NF_{min}$ as a function of $V_g$ for a composite channel device. For different $V_d$, the $NF_{min}$ versus $V_g$ curves show the typical "U-shape" behavior, which could be due the bias dependence of channel noise source parameter as well as decrease in $g_m$ at low $I_d$ (i.e. $V_g$) and measured at different $V_{ds}$. The bias dependence of $NF_{min}$ of composite channel HEMT behaves differently from the control device with single InGaAs channel (Fig.2). It can be seen in the Fig.1, as the $V_d$ is increased from 0.5 to 3 V, the optimum gate voltage ($V_g$ at $NF_{min}$ minima) is shifted from -1 V to -0.3 V. This results in different $V_d$ dependence of $NF_{min}$ in different bias region shown in the inset of Fig.1. For instance, at low $V_g$=-0.8 V, increase in $V_d$ causes an increase in $NF_{min}$. However, at $V_g$=0, lower $NF_{min}$ is presented at higher $V_d$ region. For the single channel HEMT shown in Fig.2, the increase in $V_d$ only results in a drastic increase in $NF_{min}$ without noticeable shift of the optimum gate voltage. As shown in the inset of Fig.2, the $V_d$ dependences of $NF_{min}$ at different $V_g$ present similar trend. In fact, compared to single InGaAs channel HEMT, the device with an InGaAs/InP composite channel exhibits a relative weak $V_d$ dependence of the minimum $NF_{min}$. It can be explained by the role of the composite channel played. At higher the gate and source to drain bias, the current switches to the InP subchannel, and InP as channel material will have a lower noise figure than that of InGaAs channel. Therefore, for the composite channel HEMT devices, at higher bias, the device will be better performance in noise figure.

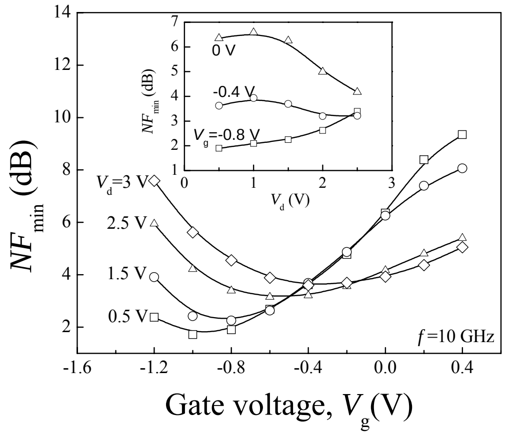


Fig.1 $NF_{min}$ as a function of $V_g$ HEMT at 10 GHz. Inset: $NF_{min}$ versus $V_d$ at different $V_g$ for composite channel

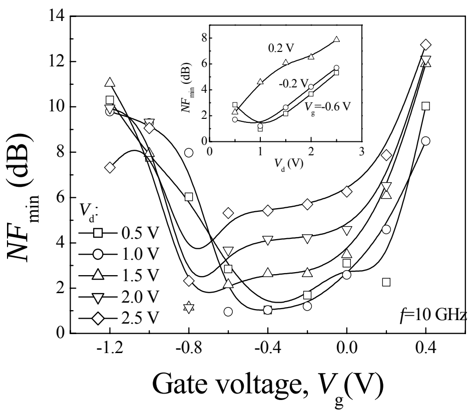

Fig.2 $NF_{min}$ as a function of $V_g$ HEMT at 10 GHz. Inset: $NF_{min}$ versus $V_d$ at different $V_g$ for single channel.

Based on a first order approximation, the $NF_{min}$ of a HEMT can be estimated using a simplified analytical expression having the basic form of [5,6,7]:

$$F_{min} = 1 + 2\frac{\omega C_{gs}}{g_m}\sqrt{K_g g_m (R_s + R_g)}$$

where $K_g$ is a fundamental noise coefficient which is related to channel thermal noise and induced gate noise. It is instructive to see than the variation of $NF_{min}$ with the change of $V_d$ could be attributed to two possibilities. One is the change of the fundamental noise thus $K_g$ due to the change of $V_d$. The second possibility could be due to the variation of device electrical parameters such as $g_m$ and $C_{gs}$, etc. However, the relation of $f_T$ versus $V_d$ for the two devices could rule out the second possibility. The $f_T$ for both devices, which is closely related to $g_m$ and $C_{gs}$ (e.g. $f_T$=$g_m/2\pi C_{gs}$), behave similarly (not shown). They increase with the increase in $V_d$. The difference on $K_g$ between the two different devices is believed to be the dominant factor for different bias dependence of $NF_{min}$. A detailed noise modeling has to be performed to further validate this explanation.

Fig. 3 shows that the channel thermal noise $\overline{i_d^2}$ and $\overline{i_g^2}$ change as a function of $V_g$ at 10GHz for the different $V_d$ extracted by modeling the composite channel device. In general, increase in $V_g$ results in the increase in $\overline{i_d^2}$. It can be seen that, the channel noise is increased if the gate bias increases. However, for different $V_d$ at $V_g$>-0.3V, when the $V_d$ is increased, the channel noise firstly increases followed by a gradual reduction for $V_d$>2.0V. Similar trend can be found at other bias condition. For example, at $V_g$=0.4V, the $NF_{min}$ has the largest value at $V_d$=1.5V. Further increase in $V_d$ results a decrease of $\overline{i_d^2}$. Notably, the $V_d$ dependence of $\overline{i_d^2}$ in composite channel HEMTs is different from the single channel device shown in Fig. 4. For the single channel devices, the channel noise has kept the increasing tendency with the increase in $V_d$. The reduction of $\overline{i_d^2}$ with increase in $V_d$ in high Vd region can be easily explained by channel electron transfer from InGaAs channel to InP sub-channel, which effectively suppresses the impact ionization noise generated from the InGaAs channel.

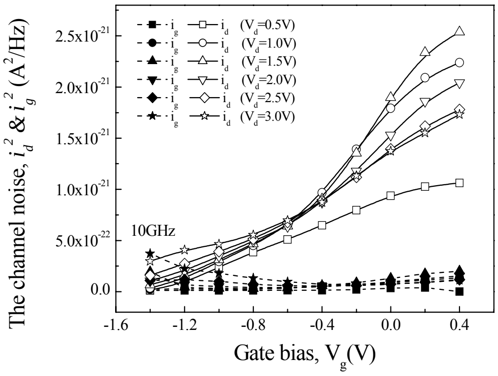

Fig.3 The extracted channel noise at 10 GHz as a function of $V_g$ for the composite channel.

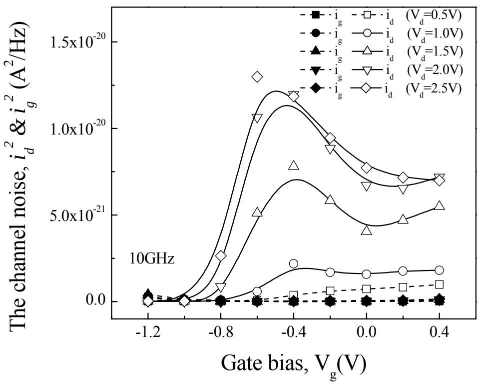

Fig.4 The extracted channel noise at 10 GHz as a function of $V_g$ for the single channel.

## IV. Conclusions

In summary, characterization of noise performance of InGaAs/InP composite channel HEMTs reveals a different bias dependence of $NF_{min}$ compared to conventional single InGaAs channel devices. The composite channel HEMT shows a lower $NF_{min}$ at high $V_d$ with a relatively weak $V_d$ dependence. This could be explained under the framework of suppression channel thermal noise due to the electron transfer from InGaAs channel to InP sub-channel at high $V_d$.

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