Device Characteristics Comparison Between GaAs Single and Double Delta-Doped Pseudomorphic High Electron Mobility Transistors

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Abstract: The $Al_{0.24}Ga_{0.76}As/In_{0.22}Ga_{0.78}As$ single delta-doped PHEMT (SH-PHEMT) and double delta-doped PHEMT (DH-PHEMT) are fabricated and investigated. Based on the employment of double heterojunction, double delta doped design, the DH-PHEMT can enhance the carrier confinement, increase the electron gas density, and improve the electron gas distribution, which is beneficial to the device performance. A high device linearity, high transconductance over a large gate voltage swing, high current drivability are found in DH-PHEMT. These improvements suggest that DH-PHEMT is more suitable for high linearity applications in microwave power device.

Key words: pseudomorphic high electron mobility transistor (PHEMT); delta dope; linearity
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1 Introduction

Pseudomorphic high electron mobility transistor (PHEMT) is one of the best technologies for power amplifiers in the frequency range of 10 to 100GHz. The delta-doped PHEMT has attracted much more attention recently and become an alternative to traditional uniformly doped PHEMT in application of microwave circuit systems such as direct broadcasting satellites, microwave communication, and radar systems[1]. The key merits of δ doped PHEMT are high breakdown, high current drivability, high transconductance, high carrier mobility, and easy to control the threshold voltage[2,3]. Now there are two kinds of most widely used PHEMT design. One is single δ doped PHEMT (SH-PHEMT) and the other is double heterojunction, double δ doped PHEMT (DH-PHEMT). Both of these two kinds of PHEMT have wide applications, but a detailed performance comparison of these two kinds of devices is still limited[4]. In this study, a detailed comparison is carried out for both of these devices fabricated in our GaAs research product line. Especially, we focuse on the device linearity comparison to demonstrate the linearity improvement by the DH-PHEMT design.

2 Device structure and fabrication

Both $Al_{0.24}Ga_{0.76}As/In_{0.22}Ga_{0.78}As$ SH-PHEMT and $Al_{0.24}Ga_{0.76}As/In_{0.22}Ga_{0.78}As/Al_{0.24}Ga_{0.76}As$ DH-PHEMT were grown by molecular beam epitaxy (MBE) system on (100)-oriented semi-insulating GaAs substrates. Figures 1 and 2 show the device cross section of the investigated SH-PHEMT and DH-PHEMT respectively. Both devices are composed of a 12nm $In_{0.22}Ga_{0.78}As$ channel layer with 2nm undoped $Al_{0.24}Ga_{0.76}As$ spacer lay-

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er, a top silicon δ doping plane, and a 30nm undoped $Al_{0.24}Ga_{0.76}As$ Schottky layer and a 50nm n^+ GaAs cap layer doped $5\times10^{18}cm^{-3}$. SH-PHEMT has a top silicon δ doping of $5\times10^{12}cm^{-2}$ for electron supply. While DH-PHEMT has a top silicon δ doping of $4\times10^{12}cm^{-2}$ and additional 4nm undoped $Al_{0.24}Ga_{0.76}As$ spacer layer and a bottom silicon δ doping of $1.5\times10^{12}cm^{-2}$ below the channel.

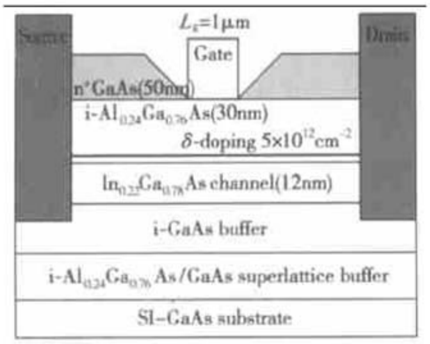

Fig. 1 Device cross-section of SH-PHEMT

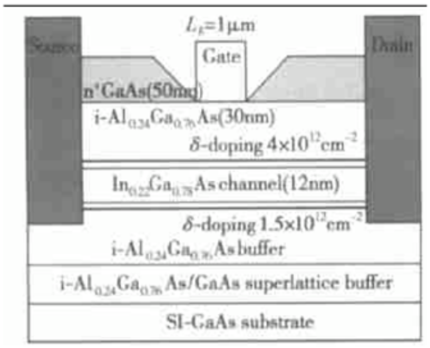

Fig. 2 Device cross-section of DH-PHEMT

The 1μm gate length, 120μm gate width both SH-PHEMT and DH-PHEMT were fabricated in our GaAs research product line. The drain to source spacing of both devices is 5μm. After the mesa isolation, Ohmic contact was first formed by depositing Ni/Ge/Au/Ge/Ni/Au six layers and followed by a short rapid thermal annealing cycle at 420℃. The 1μm gate recess was defined by the contact photolithography and was carried out with wet etching using citric based solutions. By controlling the etching time, the gate etch depth of the PHEMT can be controlled to obtain the desired threshold voltage. Ti/Pt/Au metals were then e-beam evaporated to form Schottky gate. Silicon nitride(Si_3N_4) and silicon oxide(SiO_2) were used for device passivation and were deposited by plasma enhanced chemical vapor deposition(PECVD).

3 Results and discussion

Figure 3 shows the comparison of the I_{ds}-V_{ds} output characteristics between the SH-PHEMT and DH-PHEMT. As compared to SH-PHEMT, we can observe a dramatic increase in saturation current ($V_{gs}=+1V$) for DH-PHEMT, namely from 333mA/mm to about 485mA/mm. The larger output current in DH-PHEMT is due to the double δ doped design to increase the two dimension electron gas(2DEG) density in the channel. Also the double heterojunction structure is beneficial for the 2DEG confinement.

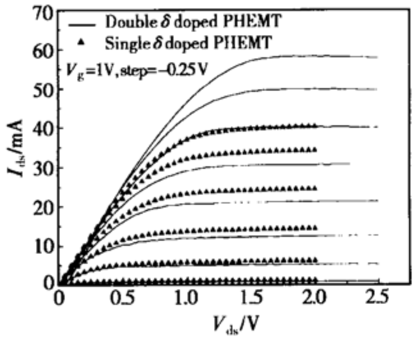

Fig. 3 DC output I_{ds}-V_{ds} characteristics of both SH-PHEMT and DH-PHEMT

The I_{ds} versus V_{gs} transfer characteristics of both SH-PHEMT and DH-PHEMT are shown in Figs. 4 and 5. Figure 4 shows the two kinds of these devices with different threshold voltage (V_{th}) and Figure 5 shows the two devices with nearly the same threshold voltage.

From Figs. 4 and 5, we can also find the high current supply in DH-PHEMT. In Fig. 4, the threshold voltage of SH-PHEMT is about $-0.4V$, while the threshold voltage of DH-PHEMT is about $-0.9V$. The slope of the two curves in Fig. 4 are nearly the same but the I_{ds} of DH-PHEMT is always higher when V_{gs} is the same. In Fig. 5, though the threshold voltage of two devices is the same (− 1.3V), but obviously the slope of the DH-PHEMT is higher and results in higher output current again when biased at the same V_{gs}.

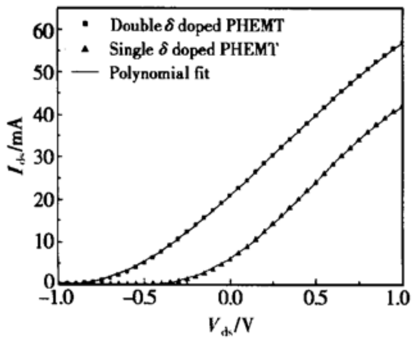

Fig. 4　I_{ds}-V_{gs} characteristics of both SH-PHEMT and DH-PHEMT with different V_{th}

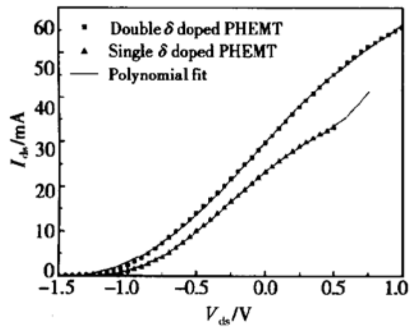

Fig. 5　I_{ds}-V_{gs} characteristics of both SH-PHEMT and DH-PHEMT with the same V_{th}

It can be found higher I_{ds}-V_{gs} curve linearity of DH-PHEMT in both Figs. 4 and 5. To further characterize these linearity properties, we use the polynomial curve fitting technique to investigate these transfer characteristics. We express the I_{ds}-V_{gs} curve by a 6th order polynomial form to describe the output characteristics as follows[5,6].

$$I_{ds} = a_0 + a_1 V_{gs} + a_2 V_{gs}^2 + a_3 V_{gs}^3 + a_4 V_{gs}^4 + a_5 V_{gs}^5 + a_6 V_{gs}^6$$

where a_0 means I_{ds} corresponding to $V_{gs} = 0$V, and the a_n's are independent variables which can determine the linearity associated with I_{ds}-V_{gs} transfer characteristics. Tables 1 and 2 summarized the simulated results of Figs. 4 and 5, respectively. We can see from both Tables 1 and 2 with a higher I_{dss} in DH-PHEMT (20.84mA, 29.82mA respectively) than in SH-PHEMT (6.04mA, 23.25mA respectively). For a distortion comparision, a_n ($n \geqslant 2$) is normalized individually by a_1. Therefore, a_n ($n \geqslant 2$) values become a linearity index. Higher a_n ($n \geqslant 2$) values translate the deterioration of device linearites. For example, the a_2/a_1 are 1.046 and − 0.442 for SH-PHEMT in Tables 1 and 2 respectively, but only 0.187 and − 0.065 for DH-PHEMT. The rest of the a_n/a_1 values are nearly all smaller in DH-PHEMT than in SH-PHEMT. From Tables 1 and 2, we can observe that DH-PHEMT demonstrate much better linearity characteristic than SH-PHEMT, which indicates that DH-PHEMT can assure low inter-modulation distortion to suppress interference among the desired signals in digital communication systems[5].

Table 1　Comparison of distortion factors between SH-PHEMT and DH-PHEMT in Fig. 4

a_n	a_0	a_1	a_2/a_1	a_3/a_1	a_4/a_1	a_5/a_1	a_6/a_1
DH-PHEMT	20.84	36.96	0.187	− 0.257	0.046	0.031	− 0.032
SH-PHEMT	6.04	25.66	1.046	− 0.217	− 0.578	0.030	0.118

Table 2　Comparison of distortion factors between SH-PHEMT and DH-PHEMT in Fig. 5

a_n	a_0	a_1	a_2/a_1	a_3/a_1	a_4/a_1	a_5/a_1	a_6/a_1
DH-PHEMT	29.82	33.85	− 0.065	− 0.295	0.039	0.082	0.016
SH-PHEMT	23.25	24.98	− 0.442	− 0.350	0.631	1.862	0.111

Figures 6 and 7 show the comparison of the V_{gs} dependence of transconductance (g_m) curves for SH-PHEMT and DH-PHEMT in Figs. 4 and 5 respectively. When the threshold voltage of the device are different, as seen from Fig. 6, SH-PHEMT has higher maximum transconductance (338mS/mm) than DH-PHEMT (320mS/mm) because the deeper etching depth of the gate recess in the SH-PHEMT resulted in higher gate control capacity. But obviously the g_m versus V_{gs} profiles in DH-PHEMT exhibit broader plateaus over a larger gate voltage swing. When the threshold voltage of the two devices are nearly the same, DH-PHEMT then had both higher transconductance (275mS/mm) and broader g_m versus V_{gs} profiles than SH-PHEMT (254mS/mm), as can be seen in Fig. 7. These results can be attributed to the better accu-

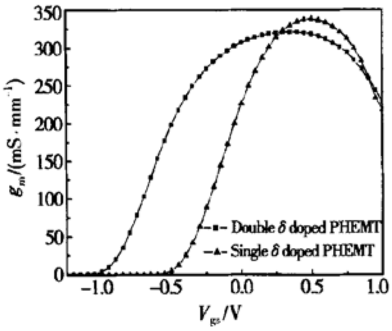

Fig. 6 g_m-V_{gs} characteristics of both SH-PHEMT and DH-PHEMT with different V_{th}

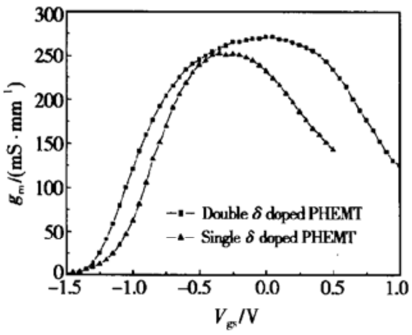

Fig. 7 g_m-V_{gs} characteristics of both SH-PHEMT and DH-PHEMT with the same V_{th}

mulation of transferred electrons in the InGaAs well with a double heterojuction, double δ doped epitaxial design in DH-PHEMT. In SH-PHEMT, only a triangular well is formed in the upper heterojunction. But in DH-PHEMT, because of the presence of heterojunctions at both sides of the InGaAs channel, the quadrate quantum well is formed instead of triangular quantum well. The transferred electrons distributed in quadrate well are more uniformly than in triangular well. And the better confinement of electron gas in quadrate well lower the possibilities of parallel conduction, which is often a more severe problem in SH-PHEMT. At the same time, the presence of the silicon δ doped planes at both sides of the InGaAs quadrate quantum well also result in higher and more uniform distribution of electron gas in the channel. So the double heterojunction, double δ doped DH-PHEMT has higher transconductance over a larger gate voltage swing, then the higher device linearity can be obtained.

Figures 8 and 9 show the comparison of g_m-I_{ds} curves for SH-PHEMT and DH-PHEMT in Figs. 4 and 5, respectively. Again, it can be found g_m distribution of DH-PHEMT is wider and uniform as compared with SH-PHEMT in both cases. These also indicate the better device linearity in DH-PHEMT than in SH-PHEMT.

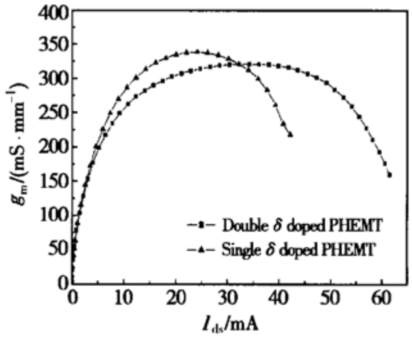

Fig. 8 g_m-I_{ds} characteristics of both SH-PHEMT and DH-PHEMT with different V_{th}

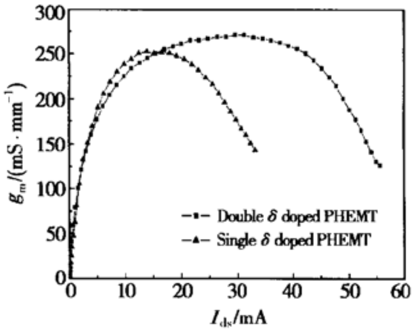

Fig. 9 g_m-I_{ds} characteristics of both SH-PHEMT and DH-PHEMT with same V_{th}

4 Conclusion

In conclusion, we have demonstrated and investigated two kinds of δ doped PHEMT (DH-PHEMT and SH-PHEMT). Due to better confinement of electrons in the quadrate InGaAs quantum well, higher electron densities, and more uniform electron distribution, it is observed that the studied DH-PHEMT has larger output current, higher device linearity, high transconductance over a larger gate voltage swing than SH-PHEMT. These advantages suggest that DH-PHEMT is more suitable for high linearity and high RF power device applications.

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双平面掺杂和单平面掺杂 PHEMT 器件的性能比较

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摘要: 研制了 $Al_{0.24}Ga_{0.76}As/In_{0.22}Ga_{0.78}As$ 单平面掺杂 PHEMT 器件 (SH-PHEMT) 和双平面掺杂 PHEMT 器件 (DH-PHEMT), 并对其特性进行了比较. 由于采用了双异质结、双平面掺杂的设计, DH-PHEMT 能将载流子更好地限制在沟道中, 得到更大的二维电子气浓度和更均匀的二维电子气分布, 这些都有利于提高器件的性能. 因此, DH-PHEMT 器件具有更好的线性度, 在较大的栅压范围内具有高的跨导和更大的电流驱动能力. 这说明 DH-PHEMT 器件更加适用于高线性度应用的微波功率器件.

关键词: 赝配高电子迁移率晶体管(PHEMT); 平面掺杂; 线性度

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