Multiple delta doping in aggressively scaled PHEMTs

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Abstract

The introduction of a second delta doping layer into the structure of aggressively scaled pseudomorphic high electron mobility transistors can dramatically enhance their performance. The results obtained from Monte Carlo device simulations show significant improvement in the device linearity when a second delta doping layer is placed below the channel. The positioning of the additional delta doping layer above the channel near the gate results in an increase in the transconductance of about 80%. In both cases the introduction of the second delta doping increases the current and hence the delivered power.

1. Introduction

Scaling of pseudomorphic high electron mobility transistors (PHEMTs) with a low indium content channel into deep decanano dimensions can dramatically improve their performance (g_m, f_T and $f_{\max}$) [1]. However, a decrease in the carrier density observed in the channel, when the gate-to-channel separation is reduced in the scaling process, has a detrimental effect on the device current, and consequently, on the device linearity. The decrease in the current can be compensated with a second delta doping layer introduced into the device structure [2]. The concentration and the position of the additional doping layer have to be carefully chosen to provide the desired effect. Monte Carlo (MC) device simulations [3] have been employed to investigate the impact of the second delta doping layer on the performance of PHEMTs with gate lengths of 120, 70, 50, and 30 nm.

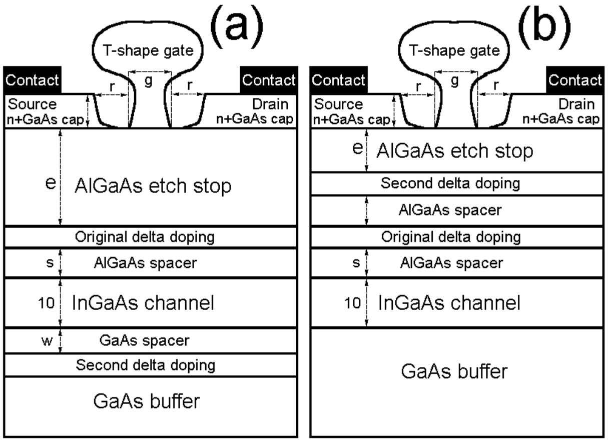

Figure 1. Cross sections of devices with two positions of the additional doping: (a) the second delta doping layer below the channel or (b) the second delta doping above the original doping layer near to the gate.

2. Double delta doped structures

The PHEMT under investigation has a typical T-shaped gate and an indium content of 0.2 in the InGaAs channel (see Fig. 1) [3].

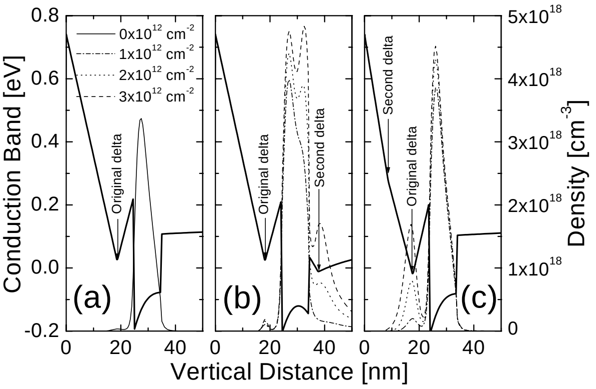

Figure 2. The conduction band profile and carrier density as functions of the depth in the 120 nm PHEMT with a single delta doping (a), with an additional layer below the channel (b), or above the channel (c).

The active doping concentration of the standard delta doping layer is assumed to be $3.5 \times 10^{12}\mathrm{cm}^{-2}$. In order to increase the carrier density in the channel, a second delta doping layer can be placed either below the channel [Fig. 1(a)] or above the original delta doping near the gate [Fig. 1(b)]. The conduction band profile of the original 120 nm single doped PHEMT [Fig. 2(a)] is compared with the profiles of the double doped structures when the second delta doping layer is placed below the channel [Fig. 2(b)] and above the channel [Fig. 2(c)].

Fig. 2 also shows that the carrier densities in the double doped structures are much higher compared to the single doped one. The carrier sheet density of $2.29{\times}10^{12}\,\mathrm{cm}^{-2}$ in the single doped 120 nm PHEMT increases to $3.61 \times 10^{12}\,\mathrm{cm}^{-2}$ in the double doped one if the concentration of the second doping is $1{\times}10^{12}\,\mathrm{cm}^{-2}$. This increase is even more dramatic for the 70 nm device where the carrier sheet density of $1.81 \times 10^{12}\,\mathrm{cm}^{-2}$ rises to $3.17{\times}10^{12}\,\mathrm{cm}^{-2}$ in the double doped device. Note that the carrier sheet density of the single doped structure calculated from the self-consistent Poisson-Schrödinger solution is precisely calibrated against measured density in material grown at Glasgow and used in the fabrication of the referenced 120 nm PHEMT.

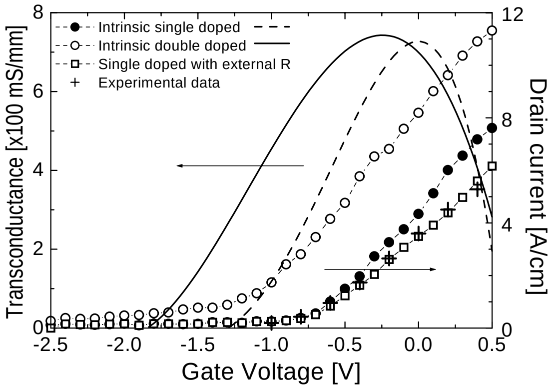

Figure 3. I_D-V_G characteristics (symbols) and transconductances (lines) of the 120 nm gate length PHEMTs. Full circles are for the single doped device and open circles are for the double doped one. The simulated data with external resistances included given by open squares are compared to the measurements by crosses.

The simulation study have been carried out using our finite element MC device simulator MC/H2F [1, 3]. To carry out a reliable study, the whole simulator has been meticulously calibrated against experimental I_D-V_D characteristics obtained from the real 120 nm gate length PHEMT [1]. The calibration procedure requires to include the contact resistances into intrinsic characteristics simulated by the MC/H2F in a post-processing stage [5].

Figure 3 demonstrates that the drain current increases twice in the 120 nm gate length double doped PHEMT in comparison with the single doped. The double doped device consists the second delta doping layer with an active concentration of $1{\times}10^{12}\,\mathrm{cm}^{-2}$ which is placed below the channel and separated by the 6 nm GaAs spacer. Although the maximum transconductance of the sin-

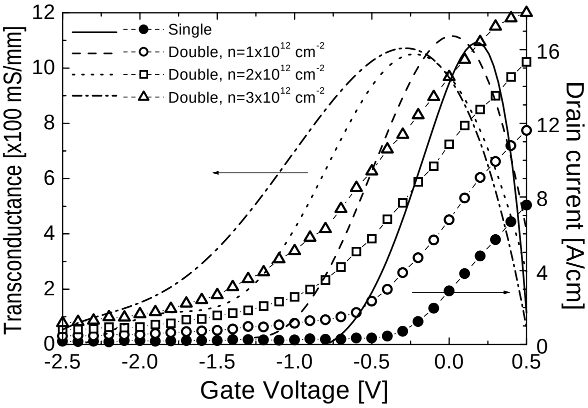

Figure 4. Intrinsic I$_D$-V$_G$ characteristics (symbols) and transconductances (lines) for the 70 nm gate length device at V$_D$ $= 1.5$ V. The double doped PHEMT has the second delta doping placed below the channel.

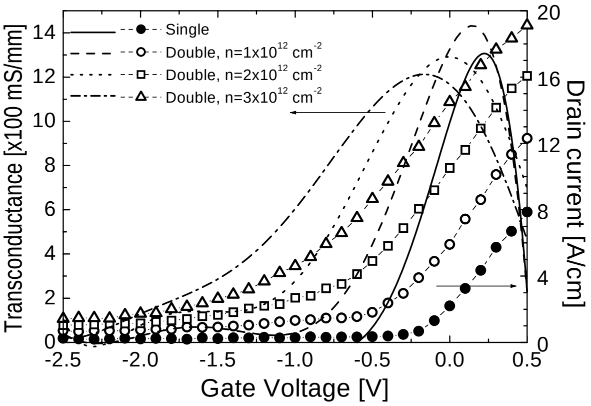

Figure 6. Intrinsic I$_D$-V$_G$ characteristics (symbols) and transconductances (lines) for the 50 nm gate length PHEMTs at V$_D$ $=$ 1.5 V, with the second delta doping layer placed below the channel.

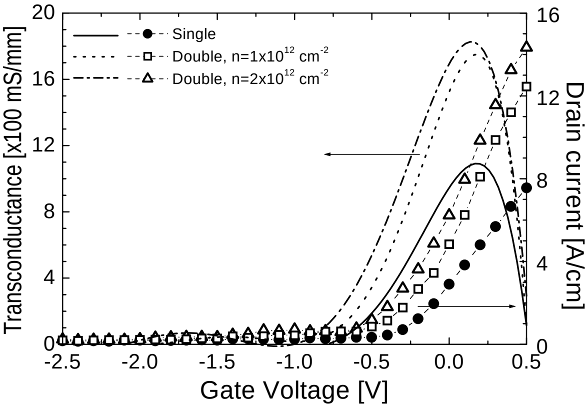

Figure 5. Intrinsic I$_D$-V$_G$ characteristics (symbols) and transconductances (lines) for the device in Fig. 4 but the double doped PHEMT has the second delta doping layer placed above the original delta doping layer.

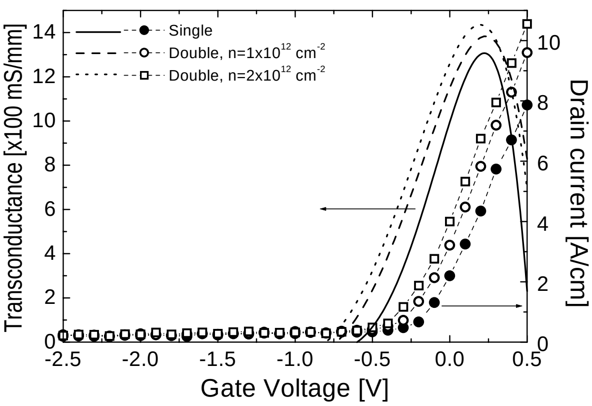

Figure 7. Intrinsic I$_D$-V$_G$ characteristics (symbols) and transconductances (lines) for the 50 nm gate length device again at V$_D$ $=$ 1.5 V when the second delta doping layer is placed above the original delta doping layer.

gle and the double doped devices are similar the double delta doping broadens g_m and improves the device linearity. I$_D$-V$_G$ characteristics and transconductances at a fixed drain voltage of 1.5 V are shown in Figs. 4 and 6 for the 70 nm and 50 nm gate length PHEMTs, respectively, with additional delta doping behind the channel. Figs. 5 and 7 provide analogous informations for 70 and 50 nm devices with the second delta doping above the channel. The current in the double delta doped PHEMTs continuously increases with the increasing of doping concentration in the second delta layer. If the additional doping is placed below the channel, the transconductance peak broadens up resulting in the large improvement in linearity of the device, although its maximum values remain close to the maximum transconductance in the single doped structure.

An effect of the second delta doping layer above the original delta doping is rather dif-

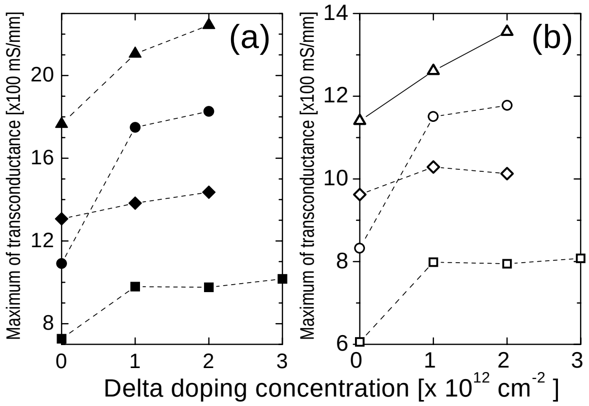

Figure 8. Maxima of transconductances versus the second delta doping concentration for an intrinsic device (a) and with external resistances included (b). Squares are for the 120 nm, diamonds are for the 70 nm, circles are for the 50 nm, and triangles are for the 30 nm gate length PHEMT. The second delta doping concentration equal to zero represents a single doped PHEMT.

ferent. The increase in the current shown in Figs. 5 and 7 is not as large as in the devices with delta doping below the channel [Figs. 4 and 6] but the maxima of transconductances are much larger (about 50% for the 120 nm, 80% for the 70 nm, and 13% for the 50 nm gate length device) than the maximum transconductance of the single doped PHEMT. This improvement in the device performance is illustrated in Fig. 8 for a set of the scaled devices. The most pronounced improvement in transconductance appears for the PHEMT with a gate length of 70 nm. The concentration used for the second delta doping does not affect the transconductance improvement except for the PHEMT with a gate length of 30 nm. When external resistances, which have been assumed to be the same as for the 120 nm single doped PHEMT, are included into calculations the magnitude of the transconductances reduce but the relative scale of improvement remains the same.

3. Conclusion

The use of a second delta doping below the channel in the scaling of PHEMTs improves the device linearity. The second delta doping above the original one, and placed near to the gate, can improve the transconductance by about 50% in the 120 nm gate length PHEMTs to nearly 80% in the 70 nm ones. At the 50 nm and 30 nm gate lengths the increase in the transconductance is less pronounced due to the small distance between the additional and the original delta dopings but an improvement is still observable. In all double doped devices the current, and hence the available power from the PHEMT, increases substantially.

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