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Transport properties of InAlAs/InGaAs/InP graded channel pseudomorphic high electron mobility structures

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Pseudomorphic $In_{0.52}Al_{0.48}As/In_xGa_{1-x}As$ heterostructures on InP (with $x > 0.53$) have emerged as excellent candidates for high-frequency field effect transistors [1]. The influence of the indium content and the channel thickness on the carrier concentration and mobility of PHEMT structures with constant In concentration has been investigated by several authors (for reference see [1]). For example, Drouot *et al.* [2] reported the electron mobility as high as $15000\,cm^2/V\cdot s$ for the carrier concentration of $2.4\times10^{12}\,cm^{-2}$ at 300 K for $InAlAs/In_{0.75}Ga_{0.25}As$ structures with a 10-nm wide channel. Another possible approach to design pseudomorphic HEMT structures is based on graded $In_xGa_{1-x}As$ channel [3]. That structure demonstrated, for instance, the electron mobility of $12700\,cm^2/V\cdot s$ for the carrier concentration of $3.0\times10^{12}\,cm^{-2}$ at 300 K.

In the present study we study the effect of the composition profile of graded $In_xGa_{1-x}As$ channel on the electron mobility. We also investigated the influence of the buffer layer on transport properties and effect of InGaAs cap layer on the results of Hall measurements.

Experimental samples were grown using a Riber 32P MBE system. The substrates were semi-insulating "epi-ready" InP(100) wafers. All the samples were grown at $500° \pm 5°C$. Lattice-matched InGaAs was used as a buffer layer for the most of structures. While an InAlAs buffer layer is typically used in InAlAs/InGaAs HEMT structures, the alternative way is to use InGaAs or InP buffer [4]. To eliminate the effect of shunting conductivity through the barrier layer, no heavily doped cap InGaAs layer was grown in the most of the structures. The thickness of the InAlAs spacer layer (4 nm) and the sheet concentration of Si atoms in δ-layer ($4\times10^{12}\,cm^{-2}$) were chosen to achieve the concentrations in the channel of about $2.5\times10^{12}\,cm^{-2}$. Hall measurements were performed on square samples using the Van der Pauw technique.

The general scheme of the investigated heterostructures is shown in Fig. 1. All graded channel structures have nearly the same compositional profile of the channel consisting of the flat part with the maximal InAs mole fraction of 0.72 with the thickness L_{flat} sandwiched between two gradient parts ($x = 0.53 \div 0.72$) with the thickness L_{grad}. Varying the values of L_{flat} and L_{grad} results in different shapes of the channel profile from pure rectangular to triangular (V-shaped).

The Hall results obtained for standard lattice-matched, pseudomorphic and graded channel pseudomorphic structures are given in Table 1. The maximal mobility observed in the lattice-matched HEMT structure was $9330\,cm^2/V\cdot s$ (sample A), whereas the use of the pseudomorphic channel allowed us to increase it up to $11700\,cm^2/V\cdot s$ (sample F).

The main difference between the graded channel and conventional pseudomorphic HEMTs is that the two-dimensional electron gas (2DEG) of graded channel structures is mostly centered in the region with higher In concentration and effectively shifted from the heterointerface. As a result of the increased separation between the 2DEG and the

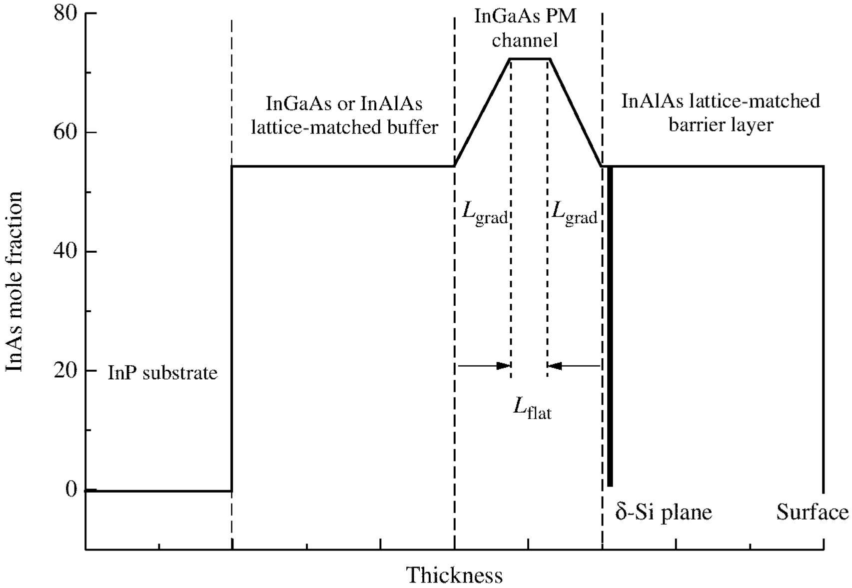

Fig. 1. Compositional profile of the investigated heterostructures.

Table 1. Structures specific parameters and the results of Hall measurements (300 K).

Sample	Channel shape	L_{grad}, nm	L_{flat}, nm	$\langle L \rangle$, nm	Δ, nm	Buffer thickness	μ, cm^2/V · s	n_s, 10^{12} cm^{-2}
A	Lattice-matched	—	—	—	—	250 nm	9330	2.45
B	V-shaped	10.2	0	10.2	10.2	230 nm	11900	2.49
C	V-shaped	10.2	0	10.2	10.2	50 nm	12400	2.60
D	U-shaped	8.7	3.7	12.4	10.6	230 nm	12800	2.53
E	U-shaped	4.4	8.3	12.7	8.6	50 nm	11000	2.64
F	Rectangular	0	13.6	13.6	6.8	50 nm	11700	2.44
G	U-shaped + cap layer	8.7	3.7	12.4	10.6	50 nm	9420	3.52

InAlAs/InGaAs heterointerface both the Coulomb scattering and the scattering due to heterointerface roughness are reduced. All graded channel structures demonstrate the mobility higher than 11000 cm^2/V · s. It is clearly seen from Table 1 that increase in the mobility well correlates with the increase in the effective separation from the interface $\Delta = L_{flat}/2 + L_{grad}$ and the effective thickness of the pseudomorphical channel $\langle L \rangle = L_{flat} + L_{grad}$ (keeping the channel thickness below the critical layer thickness). The optimal channel structure demonstrates the electron mobility as high as 12800 cm^2/V · s for the carrier concentration of 2.53×10^{12} cm^{-2} (sample D) which is among the best results ever reported for PHEMT structures.

Co-existence of two conducting paths associated with 2DEG and incompletely depleted δ-layer results in the well known reduction in Hall mobility as compared to that expected for the pure channel conductivity. However, the effect of heavily doped InGaAs cap layer is usually underestimated because the application of this cap layer leads also to strong decrease in the height of surface potential. We investigated the effect of the cap layer on the Hall measurement results. PHEMT structure G has the same design as D but, in addition, the 7-nm InGaAs cap layer heavily doped with Si ($4 \times 10^{18}\,\mathrm{cm}^{-3}$) was grown on the top. In our structures the typical sheet channel concentration from Hall measurements is $(2.4 \div 2.8) \times 10^{12}\,\mathrm{cm}^{-2}$. The appearance of some parallel conductivity through the barrier layer in the structure with cap n^+ layer results in increase in the measured Hall sheet concentration from 2.53×10^{12} to $3.52 \times 10^{12}\,\mathrm{cm}^{-2}$ and decrease in the measured Hall mobility from 12800 to 9400 $\mathrm{cm}^2/\mathrm{V} \cdot \mathrm{s}$ (samples D and G, respectively).

Most of device-oriented structures are based on an InAlAs buffer layer since the use of InGaAs leads to insufficient pinch-off characteristics due to spreading of the channel electrons over this InGaAs buffer layer. However, this problem can be effectively overcome by strong reduction of the thickness of InGaAs buffer. In this case the potential barrier at the interface of semi-insulating InP substrate prevents electron spreading.

To study the effect of the buffer layer thickness, several HEMT structures were grown on very thin (50 nm) InGaAs buffer layer. The comparison shows that the thickness of the InGaAs buffer layer can be reduced from 230 nm to at least 50 nm with no pronounced effect on concentration in the channel. At the same time, the mobility increases slightly, most probably due to the elimination of the effects of small lattice mismatch and better carrier localization in the region with high In composition.

In conclusion, we studied the effect of the composition profile of pseudomorphic channel on transport properties of InGaAs/InAlAs structures. The increase in the effective separation of 2DEG from the heterointerface and the channel thickness was shown to be the key point to achieve the maximal mobility. The possibility to achieve excellent transport properties in structures with very thin InGaAs buffer layer is shown.

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