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2DEG-based multilayer AlGaN/GaN heterostructures with lowered sheet resistance

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Abstract. The influence of n-type doping of the AlGaN barrier layer in AlGaN/AlN/GaN single- and triple-channel heterostructures on their electrical properties was studied. It was found that the optimal thickness of i-AlGaN spacer is 3 nm, and the Si concentration in n-AlGaN is $7 \cdot 10^{18}$ cm^{-3}. The lowest predicted sheet resistance at room temperature for the triple-channel structure of the optimal design is ~ 90 Ω sq^{-1}, three times lower than that of the single-channel structure.

Keywords: GaN, AlGaN, HEMT, 2DEG, multichannel

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Многослойные AlGaN/GaN гетероструктуры с низким слоевым сопротивлением на основе двумерного электронного газа

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Аннотация. В данной работе было исследовано влияние легирования барьерного слоя AlGaN примесью n-типа в одно- и трёхканальных AlGaN/AlN/GaN гетероструктурах на их электрические свойства. Установлено, что оптимальная толщина i-AlGaN спейсера составляет 3 нм, а оптимальная концентрация Si примеси в n-AlGaN составляет $7 \cdot 10^{18}$ см$^{-3}$. Наименьшее рассчитанное слоевое сопротивление трёхканальной структуры при комнатной температуре ~ 90 Ом/квадрат, что в три раза меньше, чем у одноканальной структуры.

Ключевые слова: GaN, AlGaN, транзистор с высокой подвижностью электронов, двумерный электронный газ, многоканальный

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Introduction

AlGaN/GaN-based heterostructures allow the fabrication of devices, i.e., high-electron mobility transistors and Schottky barrier diodes with high current (> 1 A/mm [1, 2]) and power (> 40 W/mm [1]) due to the unique properties of the III-N material system. The typical values of the two-dimensional electron gas (2DEG) concentration in such structure are $N_s = 1.0-1.3\cdot10^{13}$ cm^{-2} with electron mobility μ ~ 2000 cm^2 V^{-1} s^{-1}. A further increase of the concentration by increasing the Al mole fraction in the barrier layer is hindered by the strain relaxation [3]. Moreover, the 2DEG mobility is usually strongly decreases when the 2DEG density increases [4], so the conductivity remains unchanged or even becomes lower. The use of the structures with multichannel design with multiple 2DEGs could be an alternative approach to achieve higher conductivity [5, 6]. For more details on progress, benefits and drawbacks of GaN multi-channel power devices, the reader is referred to the recent review article [6]. Such design enables increasing the total electron concentration without degrading the mobility. However, strong internal polarization electric fields lead to a significant modification of the conduction band energy profile, so some channels of unintentionally doped structures could be completely depleted, and the total conductivity turns out to be significantly lower than expected. On the other hand, introducing too much dopants to the barrier layers may result in the forming of parasitic conduction channels. Therefore, design optimization is required.

In this paper, we investigated the influence of the design of single- and triple-channel AlGaN/AlN/GaN heterostructures on their electrical properties.

Model description and experimental details

A single channel heterostructure consisted of 23 nm $Al_{0.23}Ga_{0.77}N$ barrier layer, 1 nm AlN interlayer and 50 nm GaN channel and thick GaN buffer layer. In a triple channel structure, first three layers (i.e., AlGaN, AlN and GaN channel) were repeated three times. Python programming language was used to solve 1D Schrödinger-Poisson equation system [7].

Three samples were grown by metalorganic chemical vapor deposition on c-face sapphire substrates in our in-house Dragon-125 epitaxial system using trimethylgallium, trimethylaluminum, ammonia precursor gases; monosilane was used as a source of Si atoms for n-type doping. The electrical parameters of the structures were measured at several points using contactless eddy current and the van der Pauw methods.

Results and Discussion

It is known that ionized donors can scatter electrons, resulting in a lower mobility. Modulation doping technique could be used to reduce the impurity scattering. A simple expression for the scattering rate of a perfect 2DEG associated with spatially separated donors could be derived [8]:

$$\frac{1}{\tau} = N_{imp}\frac{m}{2\pi\hbar^3 k_F}\left(\frac{e^2}{2\varepsilon_s\varepsilon_0}\right)^2 \int_0^{2k_F} \frac{e^{-2qd_0} - e^{-2q(d_0+d_{Si})}}{2(q+q_{TF})^2} \frac{qdq}{\sqrt{1-\left(\frac{q}{2k_F}\right)^2}}, \quad (1)$$

where N_{imp} is a 3D concentration of donors, d_0 is the thickness of i-AlGaN spacer and d_{Si} is the thickness of the n-doped AlGaN layer. Other symbols are used in their conventional meaning in the context of carrier scattering, i.e q is the wavevector, k_F is the Fermi wavevector, q_{TF} is the Thomas-Fermi screening wavevector for 2DEG, m and ε_s are electron effective mass and relative static dielectric constant, respectively. The dependencies of the 2DEG mobility limited by ionized donor scattering and the 2DEG density versus Si concentration in the n-AlGaN for the structures with different thickness of i-AlGaN spacer are shown in figure 1. As one can see, the mobility associated with modulation doping could be as low as ~ $2\cdot10^4$ cm^2 V^{-1} s^{-1} for entirely doped AlGaN barrier. We chose 3 nm of unintentionally doped i-AlGaN spacer to ensure almost negligible impurity scattering not only at room temperature but at low temperatures as well. The 2DEG density monotonically increases with increased doping concentration. One should note that very

high Si concentrations > 7-10·10^{18} cm^{-3} result in a parasitic conduction channel in the AlGaN barrier. For moderate Si concentrations, the 2DEG density depends weakly on the thickness of the i-AlGaN spacer.

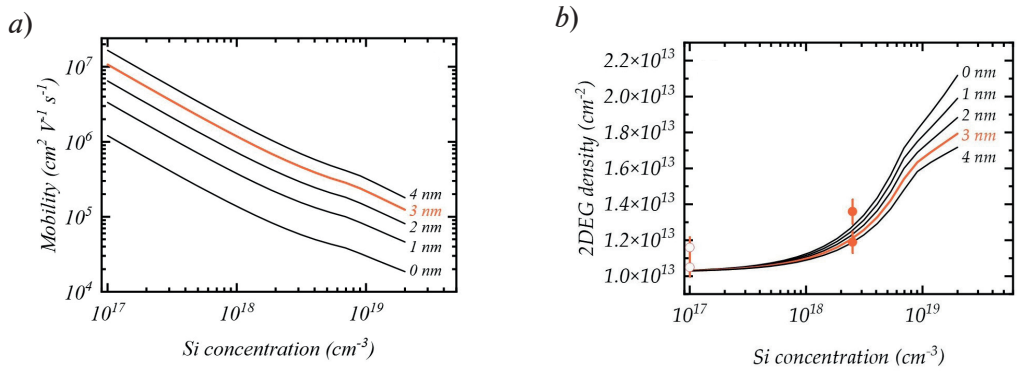

Fig. 1. The 2DEG mobility limited by remote ionized impurity scattering (*a*) and the 2DEG density (*b*) versus Si concentration in the n-AlGaN barrier in a single channel structure with different thickness of i-AlGaN spacer. Symbols are experimentally measured 2DEG density

Next, we simulated triple channel structures with the thickness of undoped i-AlGaN spacer of 3 nm. The dependence of the 2DEG density in each channel on the Si concentration is shown in Fig. 2, *a*. Interestingly, that the middle channel is almost depleted for moderate doping concentrations, and the total 2DEG density is almost the same as for single-channel structures. The finding is consistent with the results of [5]. For the high Si concentration, the 2DEG densities in all channels become the same, but, similarly to the single channel structures, an undesirable conduction channel appears in the AlGaN barrier layer. The calculated band diagrams for the cases of unintentionally doped (10^{17} cm^{-3}) and heavily doped (10^{19} cm^{-3}) barrier are shown in Fig. 2, *b*. Therefore, the optimal Si concentration in the AlGaN barrier layer is ~ 7–8·10^{18} cm^{-3}.

It is also interesting to predict the sheet resistance R_S. In order to avoid computationally intensive calculations of the 2DEG mobility including all the relevant carrier scattering mechanisms (which, however, cannot *a priori* reproduce experimentally observed strong decrease of the

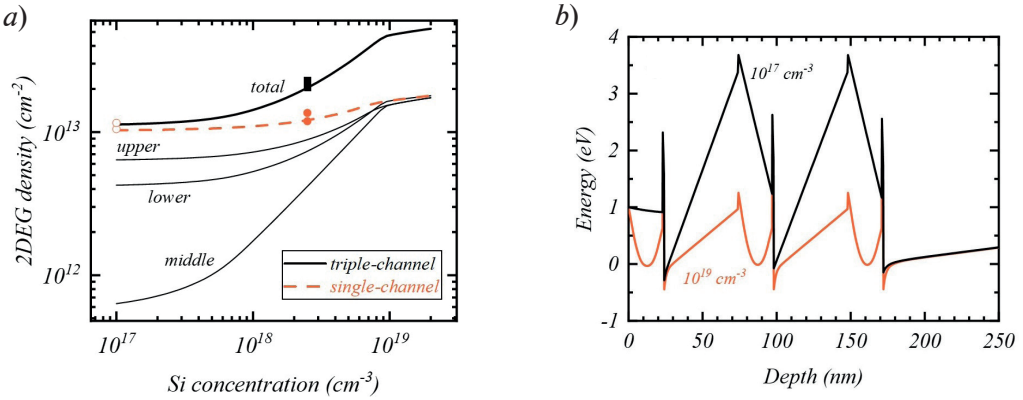

Fig. 2. The 2DEG density in upper, middle and lower channels versus Si concentration in n-AlGaN barrier layer (*a*) and conduction band energy (*b*). Dashed line is the 2DEG density in the single-channel structure. Symbols are the experimentally measured 2DEG density in unintentionally doped (open circles) and Si-doped (solid circles) single-channel and Si-doped triple-channel (squares) structures

mobility with increased 2DEG density; see [4]), we took the mobility values of the best single-channel samples grown for our previous study [9] (the inset of figure 3), fitted the data and used the obtained dependence $\mu(N_S)$ to estimate the sheet resistance of the single and triple channel structures. As one can see in figure 3, R_S for the single channel structure is almost independent on doping concentration due to reduced mobility for high 2DEG densities and 260–280 Ω sq^{-1}.

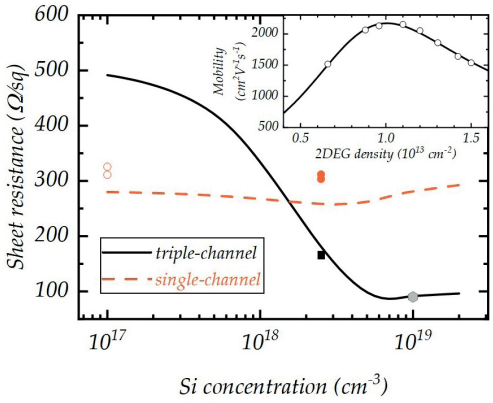

Fig. 3. The estimated sheet resistance versus Si concentration in n-AlGaN barrier layer. Symbols are experimentally measured data in unintentionally doped (open circles) and Si-doped (solid circles) single-channel and Si-doped triple-channel (squares) structures; gray hexagon is the value from [10]. The inset shows the mobility model used in the calculations (see text for more details).

A reasonable agreement with the experimental values is observed. For the triple channel one, the lowest predicted R_S is < 90 Ω sq^{-1} for Si concentration of $7 \cdot 10^{18}$ cm^{-3}. The measured R_S of our triple-channel structure is ~ 160 Ω sq^{-1} due to lower Si concentration ~ $2.5 \cdot 10^{18}$ cm^{-3} in the barrier layers. However, R_S of triple-channel structure with similar design from [10] is ~ 80 Ω/sq[1] (gray hexagon in figure 3), which is in a very good agreement with our predictions. Therefore, a simple empirical mobility fit could be effectively used to optimize the design (including automated optimization using, for example, genetic algorithm) and predict R_S of different multichannel structures at low computational cost.

Conclusion

The influence of the design of the AlGaN barrier layer on the electrical properties of single- and triple-channel AlGaN/GaN-based heterostructures was investigated. It was found that the optimal thickness of i-AlGaN spacer is 3 nm, and the Si concentration in n-AlGaN is $7 \cdot 10^{18}$ cm^{-3}. The lowest predicted sheet resistance at room temperature for the triple-channel structure of the optimal design is ~ 90 Ω sq^{-1}, three times lower than that of the single-channel structure.

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[1] Actually, the structure is four-channel: it has three main upper channels which contribute the most of the 2DEG and one lower channel with much thinner barrier with lower doping concentration, so the authors referred it as having three channels; see figures 1 and 2, *c* and the note in figure 2, *c* in the original paper [10].

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