Technology development for GaN based power microwave DHFET

A N Alexeev¹, V P Chaly², D M Krasovitsky², V V Mamaev¹,³, S I Petrov¹, V G Sidorov³ and N S Arcebashev¹,³

¹SemiTEq JSC, Saint-Petersburg, Russia
²Svetlana-Rost JSC, Saint-Petersburg, Russia
³Saint Petersburg State Polytechnical University, Saint-Petersburg, Russia
Toodayl88@gmail.com

Abstract. Key issues of epitaxial growth of III-nitrides on mismatched substrates are analysed. Thick AlN “templates” grown at extremely high temperatures and transition layers allow to reduce the dislocation density down to the order of 10⁸ cm⁻².

1. Introduction
III-Nitrides group attracted much attention for their excellent prospects for military and civil microwave electronics. Lot of microwave applications have been already developed, but the problem of a lack of native bulk material suitable for substrates is still relevant. Device passivation issues also play a significant role especially in devices degradation. In this paper we will show how some of these issues are solved at the stage of heterostructure design and growth, in particular, giving excellent electron confinement in double heterostructure field effect transistors (DHFET).

2. Experimental
III-nitride heterostructures were grown in a STE3N (SemiTeq) molecular beam epitaxy system. The main advantages of the system used are extremely high substrate temperatures (up to 1200°C) and V/III ratios (up to 1000), combined with the conventional MBE opportunities such as precise composition and thickness control etc.

The topical problem of nitrides heteroepitaxy on lattice mismatched substrates leads to a high dislocation density. There are two widespread growth methods for III-N device heterostructures: long, metal-organic chemical vapor deposition (MOCVD) and molecular beam epitaxy (MBE). The typical dislocation density of MOCVD-grown GaN layers is 1-1.5 orders of magnitude less than the one of the MBE-grown films. Moreover, this difference is due to a higher substrate temperature in MOCVD, postulated as a necessary condition for lateral coalescence of the nucleation grains at the initial growth stage.

Ammonia MBE is characterized by the tendency to increase the V/III ratio and growth temperature. However, an increase of the substrate temperature above the one corresponding to the noticeable thermal decomposition of GaN (>950°C), leads to surface roughening and to a decrease of the electron mobility [1, 2]. At the same time, the thermal stability of AlN is sufficiently higher compared...
to GaN. In turn, this allows increasing the growth temperature to high temperatures, at which the thermal decomposition of AlN is still negligible. In this context, it was suggested to grow a relatively thick AlN layer at the initial growth stage under higher temperatures that would allow to improve a coalescence of the nucleation blocks and to quickly realize the transition to the two-dimensional growth mode.

Importantly, a similar tendency is correct for the plasma assisted MBE - the method known by its «classic» approach with moderate growth temperatures and a V/III ratios close to 1. It should be noted that the increase in the temperature in ammonia MBE requires much more efforts than in PAMBE. Thus, the high temperature ammonia MBE opens the way for the growth of high quality structures for micro and optoelectronics with an active region grown further by ammonia or plasma-assisted MBE in one growth run. In particular, this approach is promising for growth of heterostructures for UV devices and microwave transistors in which high quality layers of AlN and AlGaN with high aluminum content are required.

The structural quality of this layer is extremely important for the properties of the entire subsequent structure. While growing the AlN layer, we used extremely high substrate temperatures in 1050°C-1200°C range. The increase in the crystalline quality of the multilayer heterostructure has been confirmed by STEM.

We demonstrate growth of thick AlN templates grown in the same run prior to the growth of DHFET structure. However, when growing AlGaN or GaN layers on such "thick" AlN layers, it is necessary to decrease the effect of strain, caused by the lattice mismatch. It was found that growing of AlxGa1-xN (0<x<0.5) over "thick" AlN layers followed by a strained superlattice (SL) AlxGa1-xN leads to the improvement of the morphology of the surface and structural properties, compared to growth on "thin" nucleating layers. The overall quality of GaN-based materials grown using this complex technique is competitive to MOCVD. The electron mobility in 1.5 mkm-thick Si-doped GaN layers reaches 600 - 650 cm²/Vs at the electron concentration of (3 - 5)×10¹⁶ cm⁻³ (4). The dislocation density estimated by a transmission electron microscope is less than (9 - 10)×10⁸ cm⁻² that is one of the best values ever reported for films directly grown by MBE on sapphire.

This heterostructure with a cap layer AlxGa1-xN grown on SiC substrates allows to vary the electron sheet density and mobility in a two dimensional electron gas (2DEG) in the range of (1.0-1.8)×10¹³ cm⁻² and 1300 – 1700 cm²/Vs, respectively, providing control of a 2DEG channel sheet resistance in the range of 230–400 Ω/sq. The barrier layer consists of 1 nm AlN and 24 nm AlGaN doped with Si. In case of using the AlN/GaN superlattice as a barrier layer, the thickness is 10 nm. The electron sheet concentration, mobility and sheet resistance for different barriers are shown in table 1.

| Barrier layer | n x 10¹³ cm⁻² | μ cm²/Vs | Rs Ω/sq |
|-------------|---------------|----------|--------|
| Al₀.₂₅Ga₀.₇₅N | 1.1-1.2       | 1300-1400 | 400-420 |
| Al₀.₃Ga₀.₇N | 1.5-1.6       | 1300-1400 | 290-310 |
| Al₀.₄Ga₀.₆N | 1.7-1.8       | 1300-1400 | 250-270 |
| Superlattice | 1.8-1.9       | 1500-1700 | 230-250 |
| In₀.₁₇Al₀.₈₃N | 2.3-2.4       | 1200-1300 | 210-220 |
| In₀.₁₇Al₀.₈₃N[3] | ~1.6         | 1600     | 244    |
| In₀.₁₇Al₀.₈₃N[4] | 2.27         | 1684     | 163    |

Distribution of sheet resistance in DHFET with a AlGaN barrier grown on a 3-inch substrate is shown in figure 1, the uniformity is about 1-2%. High quality heterostructures were grown using ammonia as well as plasma-assisted MBE on high temperature ammonia buffer layers.
An STE EB71 electron beam system and an STE RTA100 rapid thermal annealing system were used for Ti/Al/Ni/Au ohmic contacts metallization and annealing. The typical value of ohmic contact resistance corresponds to 0.4 - 0.5 Ω×mm. The STE ICPe68 and STE ICPd81 systems were used for mesa isolation etching and SiN, passivation, correspondingly. PCM DC-parameters include current density of 1 A/mm, maximum transconductance of 200 mS/mm, and breakdown voltages over 100V after SiN, passivation step (figure 2).

Application of this technology and DH design for growing on SiC substrates enabled one to manufacture a DHFET with a gate length of 0.5 µm for 0.03–4.0 GHz extra-broadband power amplifiers having $P_{out} = 2.5$ W, gain 17 – 25 dB and efficiency 30%. During aging tests all the devices have shown reliable operation for more than 3500 hours under 85°C. These device parameters confirm the high quality of the heterostructure and the chosen technological and design approaches.

Performance and reliability of nitride DHFET devices can be improved by replacing the barrier AlGaN layer by a InAlN one with In content of 17% lattice matched to GaN. At this composition stress and piezopolarisation are not present, potentially improving the stability of the heterostructure. At the same, the time electron density is even more because of higher difference in spontaneous polarization.

In the case of PAMBE, Me-rich growth conditions were used, fluxes of Al and In were equal to 0.3 and 0.1 um/hour correspondingly, and N flux corresponded to the growth rate of 0.37 um/hour. Alternatively, in the case of ammonia MBE N-rich growth conditions were used at extremely high ammonia flux of 1000 sccm. The main parameter for optimization in both cases is the substrate temperature. Increasing of substrate temperature leads to decreasing In content due to InN thermal decomposition. On the other hand, decreasing substrate temperature leads to a droplet formation and a transition to the three-dimension mode. It has been found experimentally that the optimal temperature is about 490°C for PAMBE and 620°C for ammonia MBE. Besides, a thin AlN layer (of several angstroms) between GaN and InAlN is very important for high quality DHFET growth. After the design and growth condition optimization, high quality GaN/InAlN heterostructures (with electron sheet density and mobility being in the range $(2.2–2.4) \times 10^{13}$ cm$^{-2}$ and $1200$–$1300$ cm$^2$/V×s, respectively) were grown using both PA-MBE and NH3-MBE at extremely high ammonia flux.

3. Summary

Extreme ammonia MBE growth regimes for as-grown AlN templates give improved quality of GaN. GaN grown on sapphire by both ammonia and PA MBE is comparable to good quality MOCVD and several times better than in conventional MBE. High quality DHFET for extra-broadband power amplifiers were fabricated. The device parameters confirm the high quality of the heterostructure and
chosen technological and design approaches. High quality GaN/InAlN heterostructures were grown using PA-MBE as well as NH3-MBE at extremely high flux of ammonia.

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