GROWTH AND CHARACTERIZATION OF ALGAN/GAN HETEROSTRUCTURES FOR ELECTRONIC DEVICES AND SENSORS

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ABSTRACT

The influence of the Si dopant concentration and its distribution through the AlGaN barrier layer of the AlGaN/GaN heterostructures on their electrical properties was studied. Three types of the heterostructures were grown by MOVPE method on sapphire substrate. Electrical properties of the $Al_xGa_{1-x}N$/GaN heterostructures were determined by the impedance spectroscopy method. The carrier concentration in AlGaN/GaN heterostructure, the incremental sheet charge concentration and 2DEG sheet charge concentration were obtained and correlated with Si dopant distribution through the AlGaN barrier layer of the heterostructure.

INTRODUCTION

The AlGaN/GaN material system is attractive for numerous device applications [1]. The relatively well developed research areas are photonic and high-power electronic devices based on nitrides. Recently, in addition to these, new trends are emerging which indicate that chemical and biochemical sensor applications of AlGaN/GaN heterostructures could benefit from unique properties of nitrides such as their excellent chemical stability and inertness as well as the possibility of formation of high-density two dimensional electron gas (2DEG) on the AlGaN/GaN hetero-interface, even without intentional doping. Its existence near the heterostructure surface is extremely beneficial for highly sensitive detection of surface phenomena. Nitrides heterostructures are also one of the leading candidates for high frequency application up to THz range (regime). However, up to now the parameters of AlGaN/GaN heterostructures do not reached the predicted, theoretical, values. Because of the lack of commercially available bulk GaN substrates the AlGaN/GaN heterostructures are typically grown on sapphire, SiC or Si substrates. The very large mismatch of lattice parameters and thermal expansion coefficients between nitrides and these substrates causes many problems during the growth and influenced the quality of the heterostructures. The choice of the substrate results from the applications and it strongly determines the properties of AlGaN/GaN heterostructures. The

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basic theoretical correlations between the thicknesses and composition of AlGaN barrier layer, its doping level and spontaneous and piezoelectric polarization are relatively well established. It was shown that the Al content in the AlGaN barrier of the heterostructure influenced mainly spontaneous and piezoelectric polarization and its breakdown voltage [2]. The optimization of MOVPE (Metalorganic Vapour Phase Epitaxy) growth process parameters optimization was studied extensively [3-5]. It was established that the MOVPE system configuration as well as the details of the growth process strongly influenced the obtained results. Additionally, our previous study has shown that that the 2DEG parameters at the AlGaN/GaN heterointerface are not influenced by the parameters of HT GaN buffer layer in a wide range of its carrier concentration [6]. It is in a good agreement with recently published results [7]. But till now it seems that many unidentified factors exist that influence the electrical properties of the AlGaN/GaN heterostructures. One of them is the distribution of Si dopant in AlGaN barrier which influences on the 2DEG parameters at AlGaN/GaN heterointerface. To study these phenomenon three sets of AlGaN/GaN heterostructures were grown by MOVPE in which the AlGaN layer of AlGaN/GaN heterostructure was divided into three sub-layer of different thickness and different Si dopant concentration. The laser interferometr with 635 nm laser diode was used for *in-situ* characterization of the whole process growth mechanism. The electrical parameters of the heterostructures were evaluated by impedance spectroscopy method using the procedure work-out by us and verified by others [8,9]. The electrical properties of AlGaN/GaN heterostructures such as the carrier concentration in AlGaN/GaN heterostructure and the sheet carrier concentration of 2DEG were evaluated and correlated with Si dopant distribution through the AlGaN barrier layer of the heterostructure.

EXPERIMENTAL

Si doped and un-doped AlGaN/GaN heterostructures were grown on c-plane sapphire substrates by using 3×2″ Thomas Swan Close Coupled Showerhead MOVPE system at 100 mbar. Trimethylgallium, Trimethyalumi-num and NH_3 were used as a Ga, Al, and N source respectively, and monosilane (SiH_4) was used as a n type dopant. H_2 was used as a carrier gas.

The growth was performed at six main stages: 1 - sapphire substrate annealing in hydrogen atmosphere, 2 - substrate nitridation in the mixture of H_2 and NH_3 (1:1), 3 - low temperature growth of GaN nucleation layer (LT-GaN NL) at 530°C, 4 - coalescence of LT – GaN NL during temperature ramping, 5 - growth of high temperature GaN buffer layer at 1035°C, 1000 V/III molar ratio, 6 -growth of undoped and/or Si-doped AlGaN layer at 1060°C, 1200 V/III molar ratio. The schematic drawings of the MOVPE process sequence for all sets of samples are presented in *Fig. 1.* The laser interferometer with 635 nm laser diode was used for *in-situ* characterization of the growth process that allowed us to evaluate the thickness of individual layers. Three sets of samples, with different AlGaN sub-layers, were fabricated on 2,5 μm optimized HT-GaN buffer grown on LT-GaN nucleation layer [6]. The designed arrangement of AlGaN barrier sub-layer in individual heterostructure is shown in *Fig. 2*.

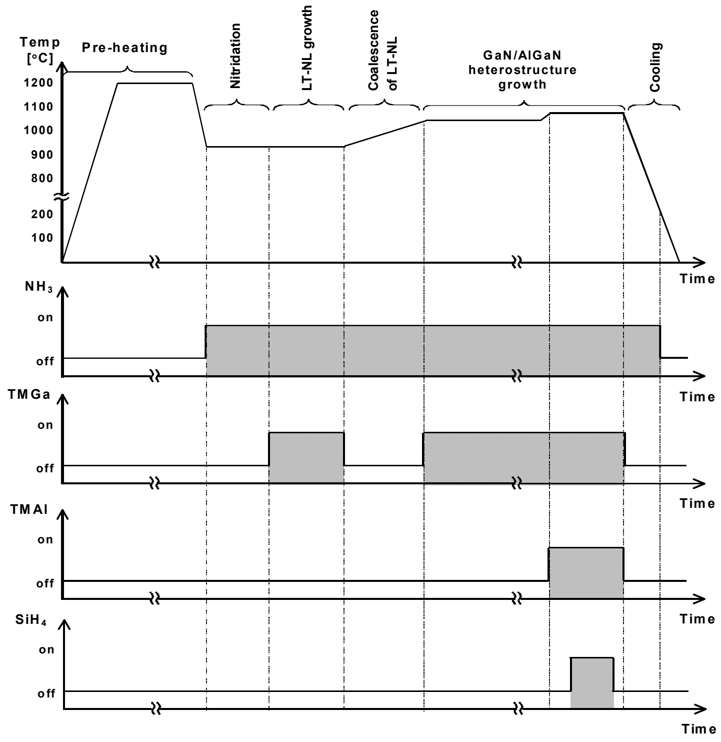

Fig. 1 – The schematic drawing of the MOVPE process sequence of AlGaN/GaN heterostructures grown on LT- GaN NL

The AlGaN/GaN heterostructures #045 consists of, looking from top to bottom, 25 nm thick undoped $Al_{0.2}Ga_{08}N$ barrier grown on 2,5 μm thick undoped high resistive HT-GaN buffer. In $Al_{0.2}Ga_{08}N$ heterostructures #042 barrier layer was divided in to two sub-layers, from top to bottom, 10 nm thick undoped $Al_{0.2}Ga_{08}N$ sub-layer and 15 nm thick Si-doped $Al_{0.2}Ga_{08}N$ sub-layer (Si concentration was $2{,}1*10^{18}$ cm^{-3}). The barrier layer of $Al_{0.2}Ga_{08}N$ heterostructures #044 was divided in to three sub-layers, from top to bottom, 5nm thick undoped $Al_{0.2}Ga_{08}N$ sub-layer, 20 nm thick Si-doped $Al_{0.2}Ga_{08}N$ sub-layer (Si concentration was $4.2*10^{18}$ cm^{-3}) and 2 nm thick undoped $Al_{0.2}Ga_{08}N$ sub-layer.

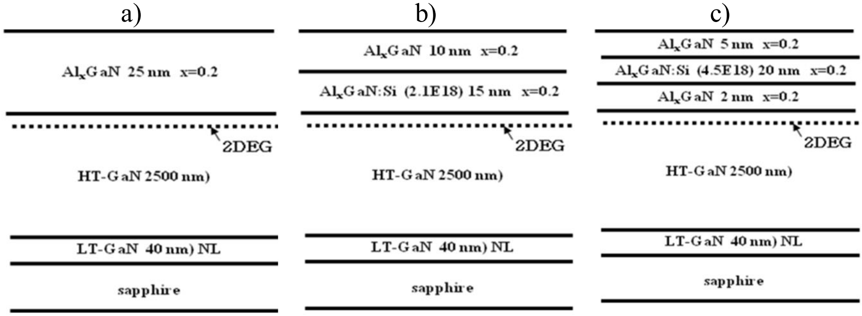

Fig.2. – The schematic cross section of AlGaN/GaN heterostructures: # 045 (a), # 042 (b) and # 044 (c)

RESULTS AND DISCUSSION

Electrical properties of the $Al_xGa_{1-x}N$/GaN heterostructures were determined by the impedance spectroscopy method performed in the range of frequencies from 80 Hz to 10 MHz with a HP 4192A impedance meter, using a two contact mercury probe. The capacitance and conductance versus frequency characteristics of the Schottky contact to AlGaN/GaN heterostructures were measured over a range of DC biases and the results were fitted to a worked-out model. The distributed elements equivalent circuit model regarding the series resistances and the Schottky junction admittance was used to evaluate the electrical properties of AlGaN/GaN heterostructures [8]. The carrier concentration distribution through the epitaxial structure and the incremental sheet charge concentration versus bias voltage were obtained for every set of the samples (*Fig. 3, Fig. 4* and *Fig. 5*).

In *Fig. 3* the carrier concentration distributions through the AlGaN/GaN heterostructures versus the distance from their surfaces are shown. In all heterostructures the characteristic spikes of the concentration at AlGaN/GaN interface, caused by 2DEG formation, were observed. For detailed analysis the excerpt of the initial part of the Figure 3 is presented in *Fig. 4*. The incremental sheet charge concentration in AlGaN/GaN heterostructures versus bias voltage is shown in *Fig. 5* that illustrates the depletion of the channel with voltage. Based on data shown in *Fig. 3* and *Fig. 5* the 2DEG sheet carrier concentration and pinch off voltage of every AlGaN/GaN heterostructure could be evaluated. In the Table 1 the values of incremental sheet charge concentration (Δn_s), the 2DEG sheet charge concentration (n_s), pinch of voltage (U_p), average mobility ($\bar{\mu}$) and maximum mobility ($\mu_{\max}$) measured and evaluated for all the studies AlGaN/GaN heterostructures are summarized.

Table 1 – Electrical characteristic of the heterostructures

N°	Δn_s [cm^{-2}]	n_{s2DEG}[cm^{-2}]	U_p[V]	Rs [Ω]	$\bar{\mu}$ [cm/V*S]	μ_{max} [cm/V*S]
045	$2.0*10^{12}$	$2.0*10^{12}$	-0.9	1732	1708	2400
042	$3.7*10^{12}$	$3.1*10^{12}$	-1.6	1592	1055	1150
044	$6.1*10^{12}$	$3.6*10^{12}$	-3.0	1423	719	1155

It was observed that in type #044 heterostructures the edge of depletion layer is located at AlGaN barrier and that the initial carrier concentration in AlGaN barrier (below 20 nm from the surface) is equal to the Si dopant concentration. The increase in bias voltage up to -1.1 V caused the removal of electrons from the barrier layer (*Fig. 5*). Above the -1.1 V bias voltage the removal of 2DEG electrons starts and at voltage bias equal to -3 V the channel is pinched off. From charge balance it could be seen that for type #044 heterostructures a part of formally evaluated as 2DEG electrons, with concentration equal to $6,1*10^{12}$ cm^{-2}, are electrons at AlGaN barrier with concentration $2,5*10^{12}$ cm^{-2}. The mobility of these electrons is low; they are not useful for carrier transport at the electron devices.

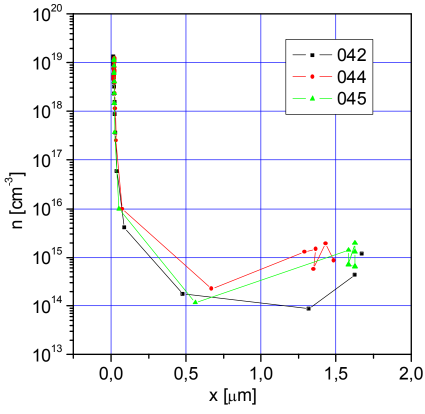

Fig. 3 – The carrier concentration distribution through the AlGaN/GaN heterostructures.

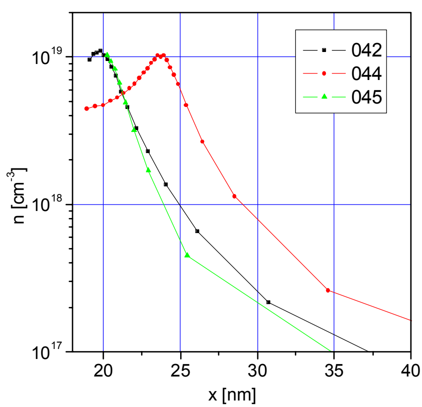

Fig. 4 – The excerpt of the initial part of the Fig. 3.

In #042 AlGaN/GaN heterostructures the total dose of the Si dopant was lower. In Figure 4 an initial increase in the carrier concentration could be observed. The value of charge at AlGaN barrier equal to $0.6*10^{12}$ cm^{-2} was measured. For this heterostructure the sheet carrier concentration of $3.6*10^{12}$ cm^{-2} was obtained. It means that the 2 DEG sheet carrier concentrations was $3.0*10^{12}$ cm^{-2}. It seems that for these MOVPE process conditions it is the maximum value of 2 DEG concentration that could be obtained in Si doped $Al_{0.2}Ga_{08}N$/GaN heterostructure with Al content in the barrier equal 20%.

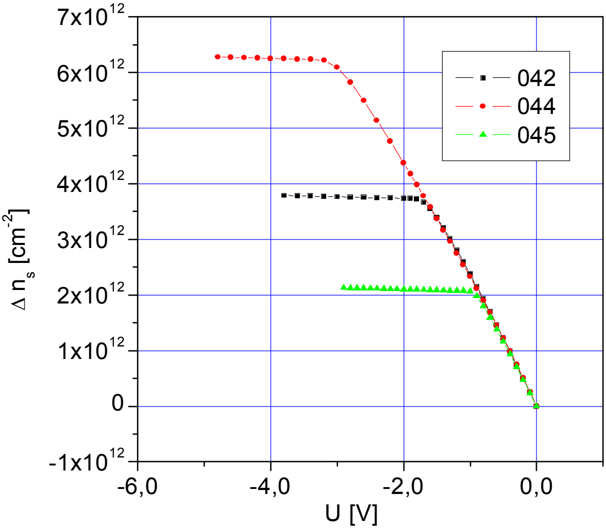

Fig. 5 – The incremental sheet charge concentration versus voltage bias in AlGaN/GaN heterostructures

In undoped AlGaN/GaN heterostructures #045 the measured sheet carrier concentration, equal to $2.0*10^{12}$ cm^{-2}, arising from the equilibrium between the charges of surface states, the charges in the channel and the charges induced by spontaneous and piezoelectric polarization.

The performed experiments showed that for $Al_{0.2}Ga_{08}N$/GaN heterostructure the maximum 2 DEG sheet carrier concentration could be obtained in the range from $2.0*10^{12}$ cm^{-2} (undoped heterostructures) to $3.6*10^{12}$ cm^{-2} (Si-doped heterostructures). The increase in the Si dopant concentration above ~ $2.0*10^{18}$ cm^{-3} is not efficient. It results in the increase of concentration of the carrier with low mobility that is useless for the electronic devices.

CONCLUSION

The influence of the Si dopant concentration and its distribution through the AlGaN barrier layer of the MOVPE AlGaN/GaN heterostructure on carrier concentration in the channel was studied using impedance spectroscopy measurement. It was found that for appropriate Al concentration at AlGaN barrier the optimum concentration of Si dopant exists which allows us to obtain the heterostructures with good electrical properties. Too high concentration of the Si-dopant could result in decreasing the 2DEG carriers' mobility.

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