

AlGaN/GaN heterostructures for hot electron and quantum effects

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Abstract. This paper reports on the transport and material characterization of AlGaN/GaN heterostructures. We compared the overheating temperatures in the transmission line model patterned devices during normal operation and analyze their dependence on the buffer thickness in order to optimize the thermal budget of the structures. It is demonstrated that noise spectra can be used to monitor the transport mechanisms and determine the activation energy of the traps. Small-dose gamma irradiation is used as an effective treatment for improving the structural properties. Based on cathodoluminescence and X-ray diffraction spectra shape, we explain the improvement as a result of the relaxation of elastic strains and structural-impurity ordering in the AlGaN barrier layer under irradiation. An irreversible improvement in mobility of the electrons in the channel, controlled by a proper dose of gamma radiation treatment, at considerably reduced self-heating is promising to achieve novel quantum transport regimes on the nanoscale.

1. Introduction

Advanced electronic systems require ultra-high miniaturization and integration. Therefore novel materials such as wide band gap III-nitrides, which can be scaled to sizes three times smaller than middle gap silicon, are attracting significant attention. Barker and co-workers [1] showed that the high field velocity characteristics of the GaN-based material appear to be advantageous for high-speed applications compared to other materials. Overshoot phenomena were registered in vacuum by Collazo et al. in intrinsic AlN film using an electron spectrometer at increased electrical field in a pulse regime [2]. An optical time-of-flight technique with femtosecond resolution allowed Wraback et al. to detect an electron velocity overshoot effect [3] in an AlGaN/GaN heterojunction p-i-n structure. At high electrical field the increase in transit time was explained as the onset of negative differential resistance, which is promising for the development of high-frequency generators. In AlGaN/GaN heterostructures with high mobility electron gas at the interface of the structure scaled to nanosizes, the integer quantum Hall effect is registered [4] at 300 mK. The authors of Ref.[5] demonstrated theoretically that controlled modification of AlGaN/GaN properties may lead to an increase in electron mobility and the realization of faster transport devices. There are many factors that influence the performance of two-dimensional gas (2DEG) at the AlGaN/GaN interface. It is well known that
spontaneous and piezoelectric polarization effects in the nitride heterostructures result in ultra-high 2DEG in the channel. Interface roughness scattering and strain relaxation are identified as the factors that have a significant impact [6] on the transport properties of 2DEG at present. In addition, electron mobility dependence on scattering caused by the strain variation of the AlGaN barrier layer in AlGaN/GaN heterostructures has been established [7]. Gamma radiation treatment allows a controlled modification of the arrangement in native defects of the structure. The introduced defects may rearrange the native defect structure and stimulate strain relaxation [8], which in the case of optimized conditions results in increased mobility. Additionally, in order to realize the excellent potential of GaN-based materials on the nanoscale and utilize novel hot electron and quantum effects, the role of self-heating effects has to be investigated, which considerably influence material transport properties and screen high-field effects caused by down-scaling.

In this paper, the influence of the thickness of the buffer layer on the 2DEG transport properties in AlGaN/GaN heterostructures was investigated. Noise spectroscopy was used to monitor the self-heating effect. Cathodoluminescence (CL) spectra were measured at different acceleration voltages in order to study the depth-resolved material properties. It is found that mobility increases when the AlGaN barrier becomes partially relaxed after a small dose of gamma radiation treatment.

2. Experimental details
The investigated structures were grown by MOCVD and patterned to form transmission line model (TLM) devices. Ungated high electron mobility transistor (HEMT) structures were studied in order to avoid the non-uniform electric field redistribution introduced by the gate metal layer. The dimensions of the conducting channel were chosen in such a way as to insure a negligibly small contribution of contact resistance. The set of the samples tested included a single interface structure of Al_{0.30}Ga_{0.70}N/GaN heterostructure with a 30-nm barrier and a 3-μm-thick GaN buffer on a sapphire substrate (HEMT A), and samples with interfaces which differ from structure A by an additional 1-nm AlN spacer grown in between the 30-nm Al_{0.25}Ga_{0.75}N barrier and the 7.5-μm GaN buffer (HEMT B). Structures A and B have GaN cap layers of 4 nm and 1.3 nm, respectively. The electrical and structural performance of the samples was analyzed. Cathodoluminescence was excited using a LEO 1550 scanning electron microscope with a 3, 5 and 20 keV electron beam. Emission spectra were analyzed with a Zeiss VIS grating monochromator using a 1221 lines/mm grating blazed at 463 nm and a photomultiplier coupled to a phase-sensitive Zeiss VIS detection system. Spectra were obtained at room temperature. The I-V characteristics were measured in the steady state. Spectral noise measurements were performed simultaneously in the frequency range from 1Hz to 100KHz using a low-noise preamplifier and spectrum analyzer HP 35670A.

3. Results and discussion
In order to understand the influence that wafer design apparently has on TLM device performance, we compared the simulation results of the overheating temperature in the active region in the TLM device with a common geometry (two-layer structure: first layer – substrate, second layer - buffer) with heat sources uniformly distributed over a rectangular area of the conducting channel on top of the second layer. The temperature rise $\Delta T = T - T_0$ in the channel is related to dissipated power, $P_{\text{dis}}$ through the thermal impedance $\theta = \Delta T/P_{\text{dis}}$. The thermal impedances were obtained for $L =$25 μm using the substrate thermal conductivity, $\lambda = 0.35$ W/cmK for sapphire, and $\lambda = 1.2$ W/cmK for the GaN buffer, respectively. Our results show (figure 1a) that the temperature increase in the channel of AlGaN/GaN heterostructures has a strong dependence on buffer thickness. It should be emphasized that the overheating temperature decreases rapidly with increasing thickness of the GaN buffer layer. This result is in good agreement with measured I-V characteristics for both samples (figure 1b).
Figure 1. (a) The calculated temperature rise in the channel of the TLM device processed on AlGaN/GaN heterostructure grown on 300 μm thick substrate as a function of buffer thickness. The arrows show the thickness of HEMT A and HEMT B, respectively, (b) Measured I-V characteristics for AlGaN/GaN HEMT structures with a channel L=25 μm: (A) – for HEMT A, (B) – for HEMT B.

Noise spectroscopy is used to monitor the self-heating effect. Deviation from conventional 1/f flicker noise was observed at some transient frequency \( f_T \) with a tendency towards noise level suppression in a wide frequency range below \( f_T \) (figure 2a). It was found that the transient frequency strongly depends on dissipated power. In view of the fact that self-heating occurs, the analysis of the noise spectra in both low-frequency and transition intervals requires that the temperature increase in the channel in the AlGaN/GaN heterostructures be estimated. We estimated the temperature rise \( \Delta T \) versus dissipated power \( P_{\text{dis}} \) on the basis of the theoretical model with (i) heat-dissipation and heat-transfer modeling in the device and (ii) the self-consistent solution of coupled nonlinear equations for the channel current \( I \) and the channel temperature rise \( \Delta T \). The latter result allowed us to plot the time parameter \( \tau \), which corresponds to the frequency separating the low-frequency 1/f range and the transition region, as a function of \( \Delta T \). An exponential dependence of \( \tau \) can be clearly seen in figure 2b.

Figure 2. (a) Spectra of the current noise of AlGaN/GaN structure (HEMT A) with a channel L=25 μm, measured for different electric fields, \( E(\text{kV/cm}): 0.04, 0.09, 0.18, 0.35, 0.75, 1.52, 2.73, 3.78 \); (b) Dependence of the characteristic time on the channel overheating.
This reflects the activation process of hopping conductivity, which results in an increase in the low-frequency component of the noise. The estimated value of the trap energy is about 0.6 eV. This energy is associated with a nitrogen vacancy, which is in good agreement with literature data [9].

Transport and noise characteristics improved after a small dose of gamma radiation treatment of \(10^6\) rad. Our results demonstrate that the carrier concentration remains practically unchanged after an irradiation dose of \(10^6\) rad, while the 2DEG mobility exhibits a considerable increase. For example, room temperature mobility of HEMT A sample is 1260 cm\(^2\)/V\(\text{s}\) before gamma irradiation and is 1350 cm\(^2\)/V\(\text{s}\) after the irradiation of the sample at a dose of \(10^6\) rad. Furthermore, after such a dose of gamma radiation the reduced dispersion of \(1/f\) noise spectral density in the set of devices is revealed. This indicates an improvement of performance and reliability of the HEMT structures.

Similar changes in mobility were also registered for three other structures. For HEMT B with the highest mobility of 1859 cm\(^2\)/V\(\text{s}\) before gamma irradiation, a mobility of 2000 cm\(^2\)/V\(\text{s}\) was registered after its gamma irradiation at a dose of \(10^6\) rad. The latter is consistent with a decrease in strain accompanied by the structural ordering of defects [10].

Depth-resolved cathodoluminescence spectra were measured in order to investigate structural changes caused by gamma radiation. The depth excitation spectra for samples A and B at different electron-beam energies were calculated using the Monte Carlo simulation CASINO [11], and are shown in figure 3a,b. It can be seen that for a beam voltage of 3kV most of the energy dissipates in the AlGaN barrier region in both structures. At higher beam voltages the excitation of the buffer is dominant.

![Figure 3](image.png)

**Figure 3.** Monte Carlo simulation of energy loss per unit length \(dE/dx\) versus electron-beam penetration depth in the HEMT structures for different acceleration voltages: (solid) – 3 kV, (circle) – 5 kV, (square) – 20 kV: (a) for HEMT A, (b) for HEMT B.

The CL spectra measured before and after radiation of samples in the investigation contain two main emission peaks (see figure 4 – figure 6): a high energy peak near the band edge (BE) at 3.4 eV and an intense yellow luminescence (YL) broad band between 2.0 and 2.8 eV. In figure 4a and 4b, the CL spectra of samples A and B excited by a 3keV electron beam are shown. The higher intensity of the BE peak in the case of sample A is the direct consequence of the thicker GaN cap layer used in this sample. It should be noted that yellow luminescence demonstrates stronger intensity with respect to BE emission at small penetration depth, due to a significant contribution by luminescent sources of the barrier layer. Elsner et al. showed [12] that yellow luminescence in GaN can be explained by a gallium vacancy and its complex with oxygen positioned at the edge dislocation core. The complex is electrically active and increases the intensity of the yellow luminescence in GaN. These deep acceptors are the radiative centers and recombination is limited by the product of its whole capture cross-section and thermal velocity. According to a DLTS study [13], deep levels in GaN can have capture cross sections as large as \(10^{-14}\) cm\(^2\), and, in this case, the capture product can become larger.
than the radiative constant of the band edge. Therefore a broad YL peak can be higher than the band edge emission peak of GaN at 3.4 eV.

At the energy of 5 keV (figure 5), the magnitude of the BE peak becomes greater and the amplitude ratio of the first and second peak increases. These changes confirm that the barrier region of the structures contributes significantly to wide band emission in the energy range from 2.0 to 2.8 eV.

![Figure 4](image1)

**Figure 4.** CL spectra of HEMT structures before (black) and after (gray) irradiation obtained at an acceleration voltage of 3 kV: (a) for HEMT A, (b) for HEMT B.

![Figure 5](image2)

**Figure 5.** CL spectra of HEMT structures before (black) and after (gray) irradiation obtained at an acceleration voltage of 5 kV: (a) for HEMT A, (b) for HEMT B.

When the energy of the beam is 20 keV and most beam energy is dissipated in the GaN buffer layer the blue luminescence (BL) peak appears at an energy of 2.85 eV in both samples (figure 6). BL is termed the donor-acceptor pair in GaN, which demonstrates direct correlation with material transport properties [14]. After irradiation, an increase of CL intensity from BL and YL is observed on sample B. The uniform increase of CL intensity over the wide energy range from 1.8 to 3.2 eV can be explained by a gamma-radiation-stimulated reduction of the concentration of non-irradiative centers in the AlGaN barrier as well as in the GaN buffer layer.

The increase of BL intensity after gamma irradiation provides evidence of the reduced density of non-radiative centers. This conclusion is supported by the fact that the generated point defects are highly mobile in GaN and can easily rearrange the native defect structure. It should be noted that gamma radiation in HEMT structures can result in the generation of extra defects or the compensation and structural ordering of native defects.
Figure 6. CL spectra of HEMT structures before (black) and after (gray) irradiation obtained at an acceleration voltage of 20 kV: (a) for HEMT A, (b) for HEMT B.

The observed room temperature mobility improvement (up to 10% at a dose of $10^6$ rad) indicates that the latter is dominant during radiation-stimulated relaxation in the investigated samples.

4. Conclusions
We investigated the 2DEG transport properties in gateless AlGaN/GaN (TLM) heterostructures grown on sapphire with different thicknesses of the GaN buffer layer. The strong dependence of overheating temperature in the channel on buffer thickness was shown. The analysis of noise spectra allowed us to evaluate the activation energy (0.6 eV) of the trap influencing the transport of AlGaN/GaN 2DEG. Additionally, depth-resolved CL spectra revealed that this trap can be associated with defect states in the GaN buffer layer. CL spectra transformation of AlGaN/GaN heterostructures after gamma irradiation provides evidence of the reduced density of non-radiative centers. Furthermore, the gamma-treated devices exhibited more stable operation due to stabilization in the 2DEG transport at the AlGaN/GaN interface. The results suggest that the transport characteristics can be managed in a controlled way by using a careful design of the layer structure and active treatment in processing technology. 2DEG with improved characteristics may demonstrate novel features and can be used in devices based on the quantum effects identified.

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