ECV profiling of GaAs and GaN HEMT heterostructures

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Abstract. AlGaAs/InGaAs/GaAs and AlGaN/GaN HEMT heterostructures were investigated by means of electrochemical capacitance-voltage technique. A set of test structures were fabricated using various doping techniques: standard doping, δ-doping GaAs pHEMT and non-doping GaN HEMT. The concentration profiles of free charge carriers across the samples were experimentally obtained. The QW filling was analyzed and compared for different mechanisms of emitter doping and 2DEG origins.

1. Introduction
HEMT transistors are the fastest active elements of microelectronics and nanoelectronics. The new record results associated with the improved technology and the use of new materials, such as GaN and InP, are published regularly [1]. The range of application areas for such devices is constantly expanding beyond broadband communication and special purpose devices [2]. For example, the 2DEG channel located near the surface was found to be very sensitive to chemical adsorption. This led to the development of various HEMT-based sensors with high selectivity and sensitivity [3]. In particular, as stated in [4], “Au gated AlGaN/GaN HEMTs functionalized in the gate region with label-free 3’ thiol modified oligonucleotides serves as a binding layer to the AlGaN surface, which can detect the hybridization of matched target DNAs. X-ray photoelectron spectroscopy (XPS) shows immobilization of thiol-modified DNA that is covalently bonded with gold in the gated region. The drain source current shows a clear decrease of 115 μA, as this matched target DNA is introduced to the probe DNA on the surface, showing the promise of DNA sequence detection for biological sensing”. A similar principle is used for detecting different proteins but in this case the current changes by 4 μA [4]. The use of Sc₂O₃ in the gate region for un gated HEMTs exhibits a linear change in current by value of 37μA/pH between pH 3–10 with a resolution of <0.1 pH. Such HEMTs-based pH sensors show stable operation over the entire pH range. The results indicate that HEMTs may be successfully used for monitoring the pH solution changes between 7 and 8, the range of high interest for human blood testing [3].

Semiconductor heterostructures of modern HEMT devices are a set of epitaxial layers of heterogeneously doped materials of various composition. The improvement of such devices with the purpose of increasing operating frequencies and currents steadily leads to high requirements for reproduction accuracy of the sequence, composition, and doping level of the layers. In addition, to satisfy certain device requirements, it is necessary to create sharp impurity profiles, including the use of δ-doping. For HEMTs, it is also extremely important to achieve a balance between the emitter impurity concentration, which determines the 2DEG concentration in the channel, and the undoped layer thickness, which determines the mobility of the charge carriers and device speed [5]. Otherwise, there is a probability of shunting the channel. All this requires careful monitoring of the parameters of
heterostructures at various stages of the technological process. From this point of view, it is especially important to control the depth distribution of both the impurity and free charge carriers.

The electrochemical capacitance-voltage (ECV) profiling technique allows to obtain the concentration-depth distribution profiles of the impurity and free charge carriers. The ECV is included in SEMI standards and successfully used for the study of various semiconductor heterostructures. The measurement of homogeneously-doped semiconductor structures by the ECV technique is well known and represents a routine task. At the same time, ECV measurements of modern multilayer HEMT structures, including those with \( \delta \)-layers, require careful selection of etching parameters and an operating measurement point [6, 7].

The main purpose of this work was to study the features of the spatial distribution of free charge carriers in GaAs and GaN HEMT heterostructures, depending on the type of doping and the 2DEG channel formation mechanism.

2. Samples and experimental technique

In this work, we investigated a set of three types of HEMT heterostructures grown by MBE (figure 1). Samples 1 and 2 are single-doped GaAs pHEMT heterostructures with emitters of different types: standard (bulk) and \( \delta \)-one. The asymmetrical \( Al_{0.22}Ga_{0.78}As/In_{0.22}Ga_{0.78}As/GaAs \) quantum well (QW) of these samples had a 14 nm width and was located at depths of 39 nm and 31.5 nm, respectively. In this case, sample 1 had a sufficiently thick emitter layer. Sample 3 had a standard layer configuration for GaN HEMT device structures. In such structures, a QW is formed due to the band offset at the AlGaN/GaN interface, while the 2DEG channel is located on the side of the GaN layer. The surface emitter layer of AlGaN had a 22 nm thickness. There were very thin (1–2 nm) GaN and AlN layers grown on both sides of the emitter layer for improving the structural properties and roughness. In particular, the presence of the AlN layer leads to sufficient improvement of the GaN/AlGaN interface quality and a noticeable increase in 2DEG mobility, respectively.

![Sample layers](image)

**Figure 1.** The sequence of layers in the investigated samples.

The measurements were performed at room temperature using an ECVPro profiler (Nanometrics). For GaAs samples, a 0.1M Tiron solution was chosen as the electrolyte [8], while for GaN we used 0.2M \( H_2SO_4 \) [9]. The area of the electrolytic rectifying contact was 0.1 cm\(^2\). The etching current was maintained at a level of 0.5 mA/cm\(^2\). During ECV profiling, the samples were etched gradually with a 1 nm step, while etching of GaN HEMT was performed in a pulsed mode [10]. The frequency of an ac test signal for arsenide and nitride structures was 300 Hz and 100 Hz, respectively. In some of the experiments, an Agilent E4980A LCR meter was used [11].

The structure of HEMT consists of many layers of different materials, electrochemical etching of which occurs at different rates. Therefore, in the ECV etching process, it is important to check the amount of etched material at different stages of the measurement. The etching depth and the surface quality were verified by atomic force microscopy (Solver NEXT AFM).
3. The experimental results and discussion

In this part of the paper, the results of the measured depth distributions of free charge carriers are presented.

3.1. GaAs pHEMT

Figure 2 shows the apparent depth distribution of free charge carriers in sample 1 with bulk QW doping, measured at several measurement points. Note that an apparent profile of free charge carriers is a result of CV derivation, in contrast to the real profile obtained under equilibrium conditions (without applied bias) [12]. As could be seen from the figure, the obtained ECV data show high reproducibility. There are two concentration peaks on the measured profile. The first peak located at a depth of 30 nm corresponds to the highly doped (emitter) region, while the second one at a depth of 44 nm originates from the QW. The concentration of free charge carriers in the emitter layer is \(1.5 \times 10^{18} \text{ cm}^{-3}\), in the QW \(2 \times 10^{18} \text{ cm}^{-3}\), which corresponds to a 2DEG concentration of \(1.6 \times 10^{12} \text{ cm}^{-2}\). The results correlate well with Hall measurements, and the position of the peaks corresponds to the regions of charge carrier localization according to the structure specification. The observed slight mismatch (less than 5 nm) with respect to the position of the peak associated with the quantum well is explained by a QW skew [13]. It is important to note that the peak corresponding to the emitter layer in such structures could be registered only by the ECV technique. According to the literature, conventional CV gives only one peak (attributed to QW) in the concentration profile [14]. The presence of two peaks is explained by a smaller Schottky barrier in case of an electrolytic rectifying contact [15].

![Figure 2. Apparent profiles of free charge carriers in sample 1 (bulk-doped GaAs pHEMT), measured at 4 different measurement points.](image)

Figure 3 shows the depth distribution profile of free charge carriers in sample 2 with δ-doping, measured at several points. As above, there are two peaks in the concentration profile corresponding, in this case, to the δ-layer (29 nm) and the quantum well (37 nm). The peak concentration of free charge carriers in the δ-layer and the QW are \(3 \times 10^{18} \text{ cm}^{-3}\) and \(2 \times 10^{18} \text{ cm}^{-3}\) (\(1.6 \times 10^{12} \text{ cm}^{-2}\), respectively.

Comparing the observed profiles of free charge carriers for samples 1 and 2, it could be seen that there is no obvious advantage in using a δ-doped emitter in terms of 2DEG concentration for the considered layer configuration and doping levels. Hall measurements of these samples also show the same concentration of 2DEG in a channel for both doping techniques. However, a smaller thickness of upper layers in the case of δ-layer structure design allows to obtain a greater value of the steep subthreshold slope characteristic, and therefore better controllability for the final device at the same values of operating current and power. This also helps to reduce the cutoff bias.
Figure 3. Apparent profiles of free charge carriers in sample 2 (δ-doped GaAs pHEMT), measured at 3 different measurement points.

Figure 4. Apparent profile of free charge carriers in sample 2 (δ-doped GaAs pHEMT), measured in a wide depth range.

The measured concentration profile of free charge carriers in sample 2 over a wider depth range (up to 100 μm) is shown in figure 4. As could be seen from the figure, after the QW response, the observed concentration value monotonically decreases according to the Debye law (investigated in detail in [16]) to a semi-insulating substrate with a concentration of ~ $10^{10}$ cm$^{-3}$. Note that this is the lowest concentration of free charge carriers in a semiconductor ever measured using the CV technique.

3.2. GaN HEMT

Figure 5 shows the depth distribution profile of free charge carriers in sample 3, measured at several points. This sample is a GaN HEMT structure and typically does not need the presence of additional doping areas. Therefore, unlike the previous samples, we observe only one peak in the concentration profile. Moreover, because of the polarization effects and a larger band offset at the interface compared to GaAs, the peak on the concentration profile has a significantly larger amplitude. So, a maximum of $1.2 \times 10^{20}$ cm$^{-3}$ ($2 \times 10^{13}$ cm$^{-2}$) is located at a depth of 22 nm. Thus, even without the use of doping, GaN HEMT allows achieving 2DEG densities of more than $10^{13}$ cm$^{-2}$.

Figure 5. Apparent profile of free charge carriers in sample 3 (GaN HEMT).

A strategy that is similar to the GaAs HEMT approach is used to increase the subthreshold slope characteristic of GaN HEMTs. It means the reduction of the thickness of upper (emitter) layers (in our case, a AlGaN layer). With decreasing thickness of these layers, the magnitude of the induced electric
field also decreases, which results in a decrease in the number of charge carriers in the channel. In this case, in order to keep the same device performance, it is necessary to compensate the lost amount of the charge (due to the thickness decreasing). This problem is solved by additional Si-doping of AlGaN. Thus, the general principles of operation and the approaches to performance optimization are similar for GaAs and GaN HEMT, with the differences due solely to the nature of the 2DEG channel formation. The measured concentrations of free charge carriers in the studied samples are compared in table 1.

| Sample number | Emitter carrier concentration in maximum, cm⁻³ | QW carrier concentration in maximum, cm⁻³ | 2DEG density, cm⁻² |
|---------------|-----------------------------------------------|------------------------------------------|-------------------|
| 1             | 1.5·10¹⁸                                      | 2·10¹⁸                                   | 1.6·10¹²          |
| 2             | 3·10¹⁸                                        | 2·10¹⁸                                   | 1.6·10¹²          |
| 3             | -                                             | 1.2·10¹⁸                                 | 2·10¹³            |

4. Conclusion
In this work, a set of GaAs and GaN heterostructures were investigated using the electrochemical CV technique. The apparent depth distribution profiles for free charge carriers were obtained. The position of the emitter layer and the 2DEG concentration in the quantum well were estimated. The obtained results show high repeatability and correlate well with Hall measurements.

The comparison of the apparent profiles for free charge carriers in GaAs pHEMT structures with different types of emitter layer doping (bulk and δ-) showed identical QW filling. Despite the apparent absence of δ-doping advantages, reduced thickness of the upper layers allows to obtain a greater value of the steep subthreshold slope characteristic, and therefore the ability of better control of the final device with the same operating current and power. This also helps to reduce the cutoff bias. For one of the structures, the record minimum value of the free charge carrier concentration ever measured by the CV technique (10¹⁰ cm⁻³) was obtained.

A HEMT structure typically does not need the presence of additional doping areas. However, due to the polarization effects and a larger band offset at the interface compared to GaAs, the 2DEG density in the channel (2·10¹³ cm⁻²) is an order of magnitude higher than that in GaAs pHEMT structures.

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