Investigation of delta-doped pHEMT InGaAs/GaAs/AlGaAs structures by the electrochemical capacitance-voltage technique

G Yakovlev, D Frolov and V Zubkov
Department of micro- and nanoelectronics, St. Petersburg Electrotechnical University “LETI”, Prof. Popov str. 5, St. Petersburg 197376, Russia
E-mail: gy@etu.ru

Abstract. In pHEMT devices, a two dimensional (2D) conducting channel representing a quantum well (QW) and adjacent layers of wide-gap semiconductors are fabricated on an undoped material which provides a high mobility of free carriers in the channel. During the development of pHEMT structures it is always very important to estimate and control the free charge carriers concentration, that is not a trivial task because of its redistribution which causes changing of the electric field distribution and, respectively, the energy spectrum of states in the 2DEG channel. By using the modern ECV technique, the pHEMT InGaAs/GaAs/AlGaAs structures were investigated. Free charge carriers concentration profiles were obtained, and the location of δ-layers and the carrier concentration in the QW were estimated.

1. Introduction
Capacitance-voltage (CV) profiling is widely used to characterize semiconductor materials and structures. It is a well-known technique with highly reproducible results. Conventional CV measurements are performed by forming a metal Schottky contact on a semiconductor surface and sweeping the applied biases. However, in some semiconductor structures like pHEMT, which have top highly doped layers, the use of this technique will result in a concentration profile at a very limited depth (of around 20 nm). Because of the breakdown of the structure at high applied voltages, the necessary information about a deeply located QW stays unknown. In this case, we prefer using a modification of conventional CV, i.e. the electrochemical capacitance-voltage (ECV) profiling. Here an electrolyte is used as a rectifying contact, which could be used in a conventional CV regime, and also for controlled dissolution of the semiconductor [1] that helps to overcome the limitations mentioned above and obtain the full information about the concentration distribution [2].

During the development of pHEMT structures for the goal of enhancing the channel conductivity, the doping level and thicknesses of functional layers in its vicinity are typically been increased, however, it could lead to the shunt of the channel by these highly doped layers. Therefore, it is very important to control the redistribution of free charge carriers between the 2DEG channel and non-uniformly doped wide-band gap barriers [3]. The problem is complicated by the fact that redistribution of free carriers in a complex multilayer pHEMT structure does change, by itself, the electric field over
the structure, which in turn causes the change in the energy spectrum of the 2DEG channel and, hence, alters the carrier concentration in the channel. Commonly, the charge carrier concentration in pHEMT channels is determined experimentally by the Hall technique [4]. However, such measurements include significant errors due to difficulties in separating the contributions to the conductance of the parallel connected 2DEG channel and heavily doped regions of the wide-band gap barrier [5]. That is why we use the ECV technique for accurate measurements of free charge carrier distribution, and for estimating the true location of δ-layers and a quantum well as well as the free charge carrier concentration in their vicinity [6].

2. Samples and experimental technique
ECV concentration profiles were measured on typical InGaAs/GaAs/AlGaAs pHEMT structures, some of them were fabricated without top highly doped layers. The structures were grown on (100) semi-insulating GaAs substrates by the MBE technique. Sample #1 has two-side δ-doping, while samples #2 and #3 have only one δ-layer with a lower doping level, other specification is the same. The In0.22Ga0.78As/GaAs-QW is located at a depth of 54.5 nm and is of 12 nm width.

The measurements were performed at room temperature using a ECVPro profiler (Nanometrics). The solution of 0.2M NaOH with EDTA was used to form the electrolyte barrier with a nominal contact area of 0.1 cm². During the ECV profiling the structures were etched gradually with a 1 nm step, and the total thickness of the removed material was ~10 nm. Atomic force microscopy (AFM Solver NEXT, NT-MDT) was used to verify the etching depth and surface quality. It should be noted that for modern multilayer pHEMT structures it is ultimately necessary to make careful selection of etching parameters, as well as to consider the impact of series resistance of lightly doped layers on the capacitance measurements [7]. The ac voltage frequency and amplitude of the test signal were 300 Hz and 10 mV, respectively. To simulate the potential lineup we used our self-consistent Poisson-Schroedinger algorithm [8].

3. Experimental results and discussion
The experimental capacitance-voltage curves and derived free charge carrier distributions for sample #1 are shown in figures 1 and 2, respectively. The CV characteristics were measured after four etching steps at the depth of 0, 3, 7 and 10 nm, respectively. Note that the biases in figure 1 were measured relative to a Pt electrode. The simulated potential lineup at the equilibrium for sample #1 is also shown in figure 2.

Figure 1. CV profiles of pHEMT sample #1 measured by the ECV depletion technique.
Figure 2. Apparent charge carrier profiles and the potential lineup in pHEMT sample #1.
We could clearly distinguish the δ-layer and the 2DEG channel. In the carrier concentration profile measured without etching (the green curve in figures 1 and 2), no response from the QW was noticed. During each etching step the thickness of the cap layer decreased, making the concentration peak from the QW more pronounced. So, we may conclude that this technique can be used for optimization of cap layer thickness under the gate contact of pHEMT devices to increase the QW filling by carriers. From the obtained data it follows that the etching has no influence on the peak concentration associated with a δ-layer, while the QW response changes significantly.

The δ-layer in sample #1 locates at 35 nm under the surface and has the charge carrier concentration in the peak of \(3.7 \times 10^{18} \text{ cm}^{-3}\). The parameters characterizing the carrier distribution in the QW are summarized in Table 1. All profiles are tailing on the Debye length. From the detailed investigation of the obtained data one could conclude that there exists a small (no more than 6 nm) mismatch between the measured and expected QW locations. This could be explained, for instance, by errors in etch depth determination or by QW skewness [9].

| Etching depth, nm | QW carrier concentration in maximum, cm\(^{-3}\) | 2DEG density, cm\(^{-2}\) | QW peak FWHM, nm |
|------------------|----------------------------------|----------------|-----------------|
| 0                | -                                 | -              | -               |
| 3                | \(1.7 \times 10^{18}\)           | \(2.3 \times 10^{12}\) | 8               |
| 7                | \(2.5 \times 10^{18}\)           | \(2.6 \times 10^{12}\) | 6               |
| 10               | \(4.5 \times 10^{18}\)           | \(4.1 \times 10^{12}\) | 4               |

It should be noted that in such complicated multilayer structures the ECV technique (the standard etching mode) does not give enough resolution, particularly because all measurements are usually performed at a fixed bias. We believe that for pHEMT structures it is necessary to measure the full CV characteristic after each etch step. The resulting carrier concentration profile can be calculated in this case by superposition of CV characteristics at different etching steps, one is represented in figure 3 (the red curve).

Another structure investigated by ECV had an additional highly doped layer, in contrast to sample #1. Its carrier concentration profile obtained by the standard ECV etching mode is also shown in figure 3 (the yellow circles). As it could be seen, the standard ECV etching mode provides the possibility of getting the concentration distribution over a wide range but with some loss in selectivity in important points (one couldn’t distinctly distinguish the δ-layer and 2DEG channel responses). In this case the integration of CV curves at each etch step is preferable for improved accuracy.

**Figure 3.** Apparent free charge carrier profiles obtained by ECV in etching end depletion modes. Profile of sample 1 (the red curve) is shifted by the removed material thickness (55 nm).
The experimental CV curves and free charge carrier concentration profiles for single δ-doped samples (#2 and #3 grown in equivalent conditions) are shown in figures 4 and 5, respectively.

![Figure 4](image1.png)  ![Figure 5](image2.png)

**Figure 4.** Experimental CV profiles of pHEMT samples #2 and #3, measured by the ECV technique.

**Figure 5.** Apparent profiles of free charge carriers of pHEMT samples #2 and #3, measured by the ECV technique.

The concentration profiles presented in figure 5 show a very good coincidence that confirms the perfect reproducibility of structures during the growing process. The Delta-layer peak carrier concentration is $2.5 \times 10^{18}$ cm$^{-3}$, and for the QW it is $1.5 \times 10^{18}$ cm$^{-3}$ (2DEG density equals to $2.2 \times 10^{12}$ cm$^{-2}$). As one can see, in the case of two-side δ-doping (sample #1), if the pre-etching process takes place, the 2DEG concentration in the QW is almost twice higher than that for single-doped samples #2 or #3.

4. **Conclusion**

In complicated multilayer pHEMT structures with highly-doped δ-layers it is necessary to measure CV characteristics after each etch process and make the superposition of CV characteristics for getting the total charge carrier concentration profile with high precision. In this study several pHEMT InGaAs/GaAs/AlGaAs structures were investigated using the ECV technique. Free charge carrier concentration profiles were obtained, the location of δ-layers and the carrier concentration in the QW were estimated. It was shown that by using the ECV technique one could optimize the etched thickness of a cap layer to obtain the best concentration of free carriers in the QW of a pHEMT device. Particularly, in the case of two-side δ-doping, the ECV technique can help to determine the optimal cap layer thickness, and the 2DEG concentration in the QW can be increased significantly in contrast to the single-doped case.

**References**

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