Electrochemical capacitance–voltage measurements and modeling of GaAs nanostructures with delta-doped layers

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Abstract. The paper presents the results of electrochemical capacitance-voltage profiling and simulation of quantum-sized semiconductor structures with quantum wells and delta-doped layers based on gallium arsenide. The experimental ECV data were obtained by superposition of measured capacitance-voltage characteristics during the gradual etching of the nanostructure. As a result of simulation, the concentration distribution and energy lineups for structures with delta-layers and quantum wells in gallium arsenide were calculated. The results of simulation are in qualitative agreement with the experimental results and data found in literature.

1. Introduction
Devices based on gallium arsenide have almost achieved their limit in characteristics, but the needs of optics and high frequency electronics lead to necessity of further enhancement of their properties [1]. The alteration of the depth of the potential wells and the concentration of impurities in the barriers in order to improve the device parameters have been brought to perfection, so the actual question is the use of artificially fabricated structures such as delta-doped layers [2].

Delta-doping is the introducing a few atomic layers of very high concentrations in the matrix of semiconductor [3]. Since the electron wave functions are localized in a wider area than the thickness of a delta layer, the charge carriers move in the undoped region, thereby the scattering by ionized atoms is reduced. Often delta-doped layers are used as a source of charge carriers for quantum wells. In this case, it can significantly increase the concentration of two-dimensional electron gas in a quantum well. When producing, designing or investigating such devices, it is useful to evaluate and predict their characteristics. To do this, we have carried out a set of measurements of electrochemical capacitance-voltage (ECV) characteristics together with the self-consistent solution of the Schrödinger and Poisson equations. While the traditional capacitance–voltage (C-V) technique has a common limitation in depth of profiling due to the relatively high charge carrier concentration, the ECV method gives the possibility to overcome the problem and to obtain the carrier concentration distribution at any necessary depth. Further, to minimize the errors due to the influence of series resistance of lightly doped layers on the measured capacitance, the experimental results were obtained by the superposition of measured capacitance–voltage characteristics across the etching depth. For the simulation of concentration profiles of samples with a delta-doped layer, we chose 1DPoisson software. The results of simulation are then compared to the electrochemical carrier concentration profiles of the structures.
2. Samples and experimental technique

Two samples based on GaAs substrates were investigated, their layer sequences are shown in figure 1. Sample #1 (figure 1(a)) has a single carbon delta layer and sample #2 (figure 1(b)) has an InGaAs/GaAs quantum well (QW) and a single carbon delta layer. All the samples were grown by MOCVD at 620 °C growth process. Nominally, the undoped regions have the impurity concentration of about $10^{16}$ cm$^{-3}$. The composition of the quantum well was In$_{0.22}$Ga$_{0.78}$As, the impurity concentration in the delta layer was about $10^{19}$ cm$^{-3}$, and the concentration in the GaAs substrate was about $10^{18}$ cm$^{-3}$. In the buffer layer, the concentration increases from the value of "undoped" region to the value of the substrate.

Measurements of the concentration of the majority charge carriers in the depth of the structures were carried out at room temperature using an ECVPro profiler (Nanometrics) with a 200 W UV Hg-Xe lamp. This profiler allows etching almost all semiconductors, particularly both $p$- and $n$-type wide bandgap ones such as GaN and SiC [2, 3]. The solution of 0.1 M tyron ($C_6H_2(OH)_2(SO_3Na)_2$) was used to form an electrolyte barrier with a nominal contact area of 0.1 cm$^2$. This etch solution is a polishing one for GaAs and provides precise etching with an appropriate speed. The frequency and amplitude of the ac test signal were 300 Hz and 100 mV, respectively. The etching was performed with a 1 nm step.

For calculation of concentration profiles and energy diagrams with quantum levels we used 1D Poisson free software [4]. This software is based on self-consistent solution of the Schrödinger and Poisson equations using the difference method with some additional changes: a simple matrix transformation that will preserve the symmetry of the result matrix while allowing a variable mesh size. If the optimal nonuniform mesh is used, this method will provide a computationally efficient solution of the band profile and the electron density distributed over a large spatial dimension.

3. Experimental and calculation results and discussion

The results of modeling of charge carrier concentration profiles and the corresponding ECV-profiling for the two investigated samples are presented in figure 2. Here, the grey lines illustrate experimental results and the black lines, modeling ones. The experimental results were obtained by the gradual superposition of measuring capacitance-voltage characteristics across the etching depth. This approach allows getting the carrier distribution over a broad distance into the depth of the semiconductor and does minimize the errors due to the influence of series resistance of lightly doped layers on the measured capacitance. Experimental and calculated charge carrier profiles showed quite good coincidence, especially for the structure with a single delta-layer (sample #1). The differences between the simulations and the measurements relate to the fact that the calculations do not take into account the diffusion effects and the broadening caused by the inherent peculiarities of the ECV-technique. Also one should take into account that the recommended growth temperature is 550 °C [3], but in our case the growth temperature was 620 °C in order to grow the sharp delta-layers. So, it can be an additional reason of sharpness for the modelled profiles.
Figure 2(b) presents the measurement and calculation of concentration profiles for the structure with a delta-doped layer and a quantum well. As for sample #1, the calculation did not take into account the diffusion effects and the apparatus function of the ECV-measurement method.

![Figure 2. Experimental (gray line) and modeling (black line) charge carrier concentration profiles for sample #1 (a) and sample #2 (b).](image)

Figures 3(a) and 3(b) show the results of calculation of energy diagram and the quantization levels for light and heavy holes for the two investigated samples. It also shows how much the energy structure of the quantum well is deformed by the presence of a delta-doped layer with a high carrier concentration.

![Figure 3. Energy diagram and the quantization levels for light and heavy holes for sample #1 (a) and sample #2 (b). In both cases the position of Fermi level is taken as zero.](image)

The results of calculation of the energy diagram are presented in figure 3(b). The first five quantization levels for light holes and first five levels for heavy holes are shown. It can be concluded that heavy holes make the main contribution to the total charge carrier concentration. Indeed, the most part of carrier concentration falls in the first energy subband. As it could be seen, the first level is the heavy hole energy level [7].
If to compare figure 3(a) and 3(b) one can notice that the energy levels within the quantum size structure shift down in energy in the presence of a delta-layer. This is due to the fact that the delta-layer serves as a reservoir filling the quantum well with additional carriers, which makes the energy levels in a quantum well deeper relative to the Fermi level.

4. Conclusion
ECV-measurements give precise information about the charge carrier distribution along the nanostructure, overcoming the limitations of the common CV-technique. On the other hand, the computer modeling can clear up the fundamental properties of the energy band structure and electronic spectrum of such objects. In this study, we reported the results of ECV-measurements and simulation of concentration profiles for nanostructures with delta-layers and a single quantum well, fabricated on gallium arsenide substrates. The experimental data were obtained by the superposition of measured capacitance–voltage characteristics during the gradual etching of the nanostructure. This approach allows getting the carrier distribution over a broad distance in the depth of the semiconductor. The experimental and simulated data are in quite good agreement; the reasons for the noticed difference in results are the diffusion effects and the apparatus function of the ECV-measurement method, which could not be taken into account in the simulations.

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