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Emission processes of the interaction between the quantum well and donor delta layer in heterostructures for pHEMTs

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Abstract: We present experimental and theoretical investigations of pHEMT heterostructures with AlGaAs/InGaAs/GaAs quantum wells (QWs) and/or a delta-doped layer, which can be used as active regions in transistors operating in the 4–18 GHz frequency range. Using the electrochemical capacitance-voltage setup ECV Pro we, for the first time, experimentally observed a concentration peak from the near-surface delta layer of the pHEMT structure together with a peak of QW enrichment. The capacitance of the electrolyte-semiconductor contact was measured by Agilent LCR-meter, which was connected to the electrochemical cell of ECV Pro through a specially designed relay module. Using numerical simulation of the electronic characteristics of nanoheterostructures by self-consistent solution of Schrödinger and Poisson equations we determined electrostatic potential profiles for band edges, band offsets, quantum-confinement levels, and concentration profiles of charge carriers for the samples under investigation. The impact of delta-layer position on the confined energy levels and carrier concentration in the QW was experimentally and theoretically analyzed in detail. We determined the optimal distance between the QW and delta layer, which provides the most efficient process of supply of charge carriers to the QW. The conducted work is directed at improvement of SHF devices, allowing one to increase the gain coefficient and transconductance of transistors.

Key words: Electrochemical capacitance-voltage profiling, ECV, pHEMT, pseudomorphic structures, quantum well, AlGaAs/InGaAs/GaAs, tunneling, self-consistent solution of Schrödinger and Poisson equations

1. Introduction

Field effect high electron mobility transistors (HEMTs) with two-dimensional electron gas (2DEG) are widely utilized as high-speed active elements of microelectronic devices [1–4]. There are often reports on new records regarding the improvement of their technology and the launch of new structures. GaAs heterostructures used in pseudomorphic HEMTs (pHEMTs), designed for operation at 4–18 GHz frequencies, are of particular interest as a key part of amplifiers, frequency mixers, frequency multipliers, etc. [5–7].

Semiconductor heterostructures (HSs) for modern pHEMT devices comprise a number of epitaxial layers of nonuniformly doped materials of various compositions. Their permanent improvement results in a strengthening of the requirements for accuracy in layer reproducibility, as well as its composition and doping level. Furthermore, there arises the necessity for the creation of sharp steps in impurity concentration [8]. All of this requires careful monitoring of parameters at various technological stages. Special attention must be paid to impurity and free charge carrier distribution control [9]. Among the characterization techniques we note some

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reports on precise ECV profiling of free charge carriers into the depth of pHEMT structures grown on GaAs substrates [10,11].

When using a delta layer in a quantum-size HS, its emission interaction with a quantum well (QW) is of great importance. When a delta layer is located near a QW, it becomes an efficient supplier of charge carriers into the QW, which can enhance the efficiency of radiative recombination in light-emitting devices and improve the HEMTs' features. The amount of carriers transferred from the delta-layer region to the QW depends both on the distance between them and on temperature. With falling temperature the degree of charge carrier localization in the delta layer increases, and this reduces the probability of carrier transition to the QW. The increase in distance also reduces the probability of charge carrier transfer from the delta layer to the QW. However, a drastic reduction of the distance between the delta layer and the QW negatively affects the crystal quality of the GaAs/InGaAs heterojunction, which leads to escalation in the amount of nonradiative recombination centers.

In this work we present the investigations of GaAs-based pseudomorphic HSs with quantum wells and pHEMT structures containing delta layers. In order to investigate the impact of the delta layer on key characteristics of the QW, a complex examination of samples was carried out. The study included self-consistent numerical modeling and its comparison with experimental data obtained by various techniques and in a broad temperature range. The following parameters were determined: electrostatic potential profiles for band edges, band offsets at the heterojunction, quantum-confinement levels, concentration profiles of free charge carriers, etc.

2. Materials and methods

2.1. Sample description

We investigated a set of pseudomorphic HSs with AlGaAs/InGaAs/GaAs QWs. The samples were of two types, depending on their growth technology and QW content. The samples of the first type were grown by metal organic chemical vapor deposition (MOCVD) technique at hydrogen atmospheric pressure. The samples were divided into a HS with a single QW $In_xGa_{1-x}As/GaAs$ (x = 0.225), HS with a single carbon-doped delta layer, and HS with both QW $In_xGa_{1-x}As/GaAs$ (x = 0.22) and a carbon delta layer in the GaAs matrix. The QWs were located 150–310 nm below the surface.

The samples of the second type were grown by molecular-beam epitaxy on semiinsulating GaAs (100) substrates. The samples were single-side doped GaAs pHEMT HSs, intended for fabrication of low-noise amplifiers. The impurity concentration in the donor layers of samples was 2.5×10^{18} cm^{-3}. The QW $Al_{0.22}Ga_{0.78}As/In_{0.22}Ga_{0.78}As/GaAs$ was placed at depth 54.5 nm from the surface and had 14 nm width. Note that a smaller thickness of upper layers in the case of a delta-doped HEMT structure design allows one to obtain a greater value of the steepness in the 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 [12].

2.2. Surface morphology study using the AFM technique

First of all, we measured the samples' surface morphologies using the atomic-force microscope (AFM) Solver NEXT (NT-MDT, Russia). For all samples the morphology was studied over its whole surface and we obtained repeatable results in its various areas. Scanning areas varied from 3×3 μm^2 up to 100×100 μm^2, which is the maximum allowable scan area for the AFM-device Solver NEXT. A typical AFM image of the sample surface is presented in Figure 1. It is seen that for the scanning area of 10 × 10 mm^2 the peak-to-peak value is 2.92 nm and RMS is 0.2 nm, which shows the good quality of the surface preparation. The good surface provided high reliability of concentration measurements.

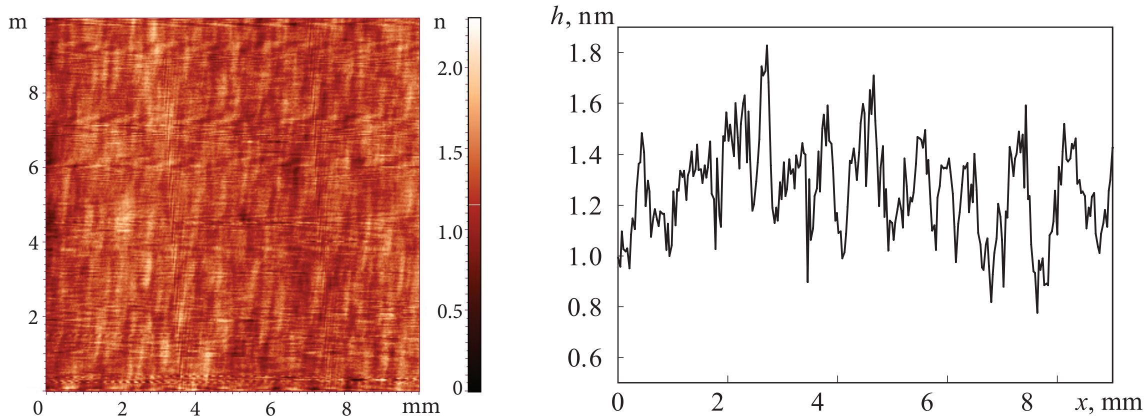

Figure 1. AFM image (a) and topography profile (b) of the GaAs sample (type II) surface.

2.3. Measurements of free charge carrier concentrations by ECV

Measurements of the distribution of free charge carriers (FCCs) into the depth of the structures were carried out at room temperature using the electrochemical profiler ECV Pro (Nanometrics). Water solution of 0.2 M Tiron was used for the creation of electrolyte rectifying contact of 0.1 cm^2 area. The etching step during ECV profiling was 1 nm. The frequency and amplitude of the ac test signal were 300 Hz and 10 mV, respectively. Etching current was ~ 0.5 mA/cm^2. In some experiments, for acquisition of capacitance-voltage characteristics in a wider frequency range (up to 2 MHz) we used an Agilent E4980A LCR-meter connected to the electrochemical cell of ECV Pro through a specially designed relay module [13]. Actually, electrochemical etching of each layer of pHEMT occurs with various speeds. Thus, during ECV etching it is important to control the amount of the etched material at the measurement stages. The use of an atomic-force microscope for monitoring etching depth and quality [14] helped us to choose the optimal measuring parameters.

2.4. Admittance spectroscopy measurements

Admittance spectroscopy was used to investigate the temperature and frequency spectra of the conductance and capacitance of the samples. Measurements of HSs with metal contacts were carried out at multifunctional computer-controlled admittance spectroscopy setup [15]. Special software was developed for supporting the setup, providing the acquisition of a multidimensional database for the measurements, including quasistatic and dynamic admittance spectroscopy methods. The setup operating temperature range is 15–475 , the frequency range is 20 Hz–2 MHz, and the biases range is 0–40 V. The recorded characteristics are majority carrier concentration, activation energy for charge carrier emission from localized levels, capture cross section, emission rate of charge carriers, etc.

Capacitance-voltage profiling for structures with Schottky barriers was performed in the temperature range from cryogenic up to 150 °C. The carrier FCC concentration profiles were obtained. Their temperature modification will be analyzed in the next section.

2.5. Self-consistent modeling

Modeling of the electronic parameters of quantum-sized HSs was carried out using the algorithm for self-consistent solution of Poisson and Schrödinger equations in a quantum box, developed earlier [16,17]. During the solution the following parameters were determined: electrostatic potential profiles for band edges, conduction and valence band offsets, quantum-confined levels in QW, and concentration profiles of free charge carriers. The calculations were carried out separately for all examined samples, both for structures with a single quantum well and for a system “QW + delta-layer”.

3. Results and discussion

3.1. ECV profiling

At present, the classical capacitance-voltage profiling technique using a Schottky barrier resolves only one peak in the concentration profile of pHEMT structures, which is attributed to a QW (2DEG channel) [18]. In ECV experiments, in contrast, we observe two peaks: from a delta layer and from a QW (Figure 2). The ability to experimentally observe two peaks is due to the fact that the liquid electrolyte used in the experiments creates a lowered rectifying contact on the semiconductor surface in comparison with the classical capacitance-voltage profiling of structures with metal contacts. Thus, the initial (at zero bias) space charge region (SCR) width appears to be smaller [19,20]. In order to prove it, we evaluated the electrolyte-semiconductor barrier height. For this goal the current-voltage and capacitance-voltage characteristics of GaAs structures of various doping levels at the contact with Tiron electrolyte of various concentrations were examined. The results are presented as a nomogram “Schottky barrier height – carrier density – concentration of electrolyte” (inset in Figure 2). It is seen that at concentration 10^{18} cm^{-3} the lowered height of the electrolyte barrier (the difference is ~ 0.25 eV) results in ~ 20 nm decrease in initial SCR width under the barrier, which corresponds to the location of the donor delta-layer in relation to the QW.

The bottom inset in Figure 2 presents the concentration profile, measured in wider depth range (up to 100 mm). It is seen that after the QW response, the apparent carrier concentration monotonically decreases according to Debye smearing [11,21] while entering the semiinsulating substrate. The free carrier concentration at the level 10^{10} cm^{-3} registered here is among the best achievements measured in semiconductors by conventional CV or ECV techniques.

Apart from the drastic reduction in capacitance, which becomes comparable with the apparatus noise, the principal difficulties in CV measuring of low-doped layers are based on the fact that SCR width becomes comparable with the sample width.

3.2. Theoretical analysis based on admittance data and numerical simulation

The theoretical analysis is based on numerical modeling with its further fitting to admittance measurements. In order to experimentally investigate the redistribution of charge carriers between the delta layer and QW with temperature change, we carried out CV measurements of FCC profiles at various temperatures.

CV characteristics and corresponding carrier concentration profiles for a structure with a single QW are presented in Figures 3a and 3b, respectively. A plateau is clearly observed in the CV characteristics, which is common for quantum sized regions with high concentration of charge carriers (QW region). The concentration profiles show the enrichment peak in the QW area. Its position denotes the geometrical location of the QW in the examined sample (305 nm below the surface). The temperature growth from 75 to 250 K resulted in a

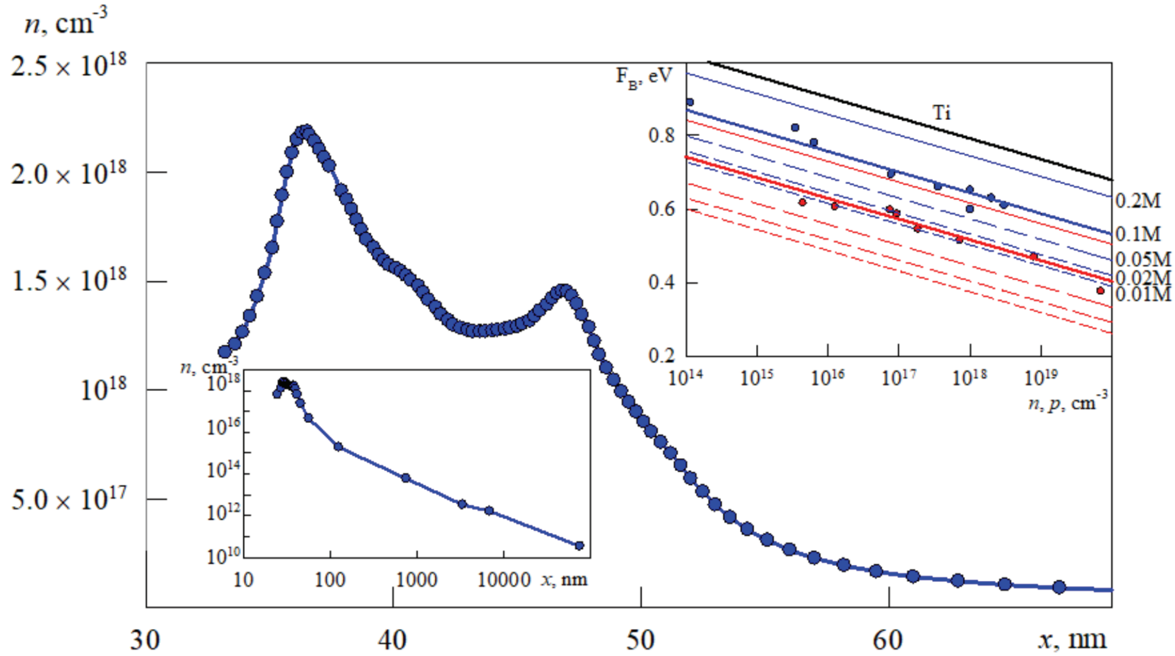

Figure 2. Concentration profile of free charge carriers in GaAs pHEMT sample with a delta-doped layer for various profiling depth ranges, and the correlation between Schottky barrier height (F_B) at the interface semiconductor-electrolyte and the free carrier concentration (n, p).

significant (around 5 times) drop in amplitude for the FCC concentration peak (Figure 3b), which is driven by an increase in probability for thermally activated emission of charge carriers from the QW. As we will show below, for a structure with a QW and a delta-doped layer it shows some weaker reduction in amplitude of the apparent charge carriers with temperature growth.

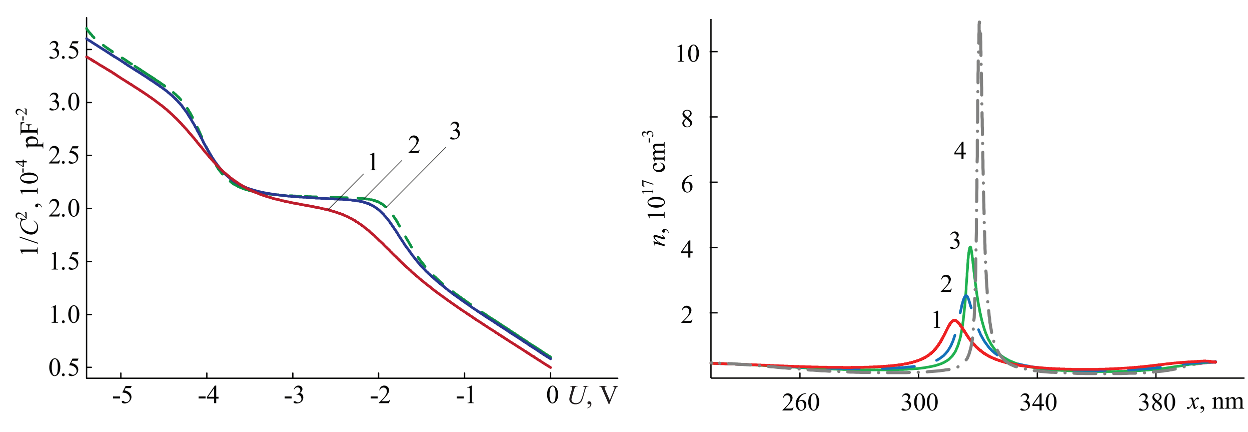

Figure 3. Capacitance investigations of the sample with a single QW $In_xGa_{1-x}As/GaAs$ ($x = 0.225$, QW width is 7.4 nm): (a) CV characteristics at various temperatures, K: 1–300, 2–155, 3–105; (b) apparent carrier concentration profile at test signal frequency $f = 1$ MHz at temperatures, K: 1–300, 2–250, 3–200, 4–75.

Figure 4 presents the CV characteristics (a) and corresponding concentration profiles (b) for samples with a carbon-doped delta layer at 10 and 296 K ($f = 1$ MHz). Similarly to that for the structure with a single InGaAs/GaAs QW, the CV characteristics show a plateau due to the presence of a delta-layer region with high charge carrier concentration.

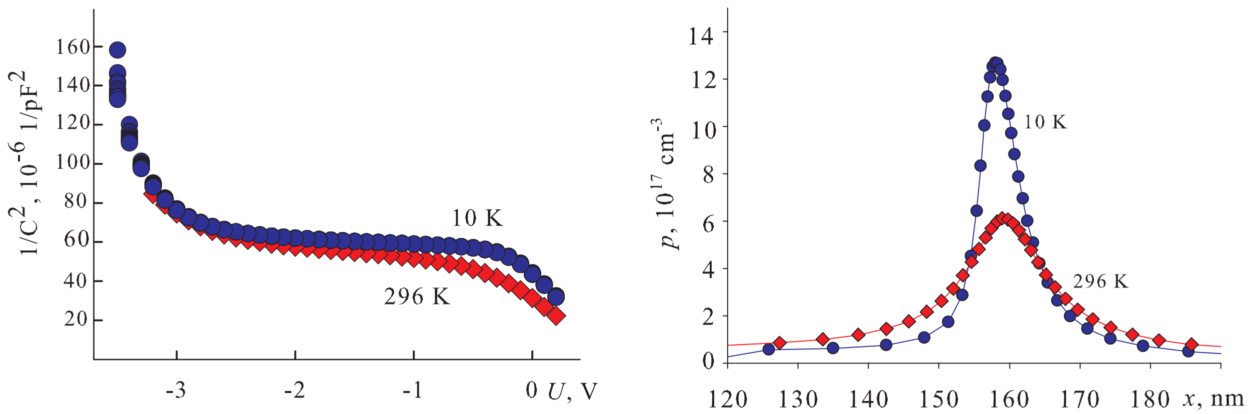

Figure 4. Capacitance investigations of the sample with a single carbon-doped delta layer at temperatures 10 and 296 K: (a) CV characteristics; (b) apparent carrier concentration profile.

The peak position in the concentration profile again denotes the geometric location of the delta layer in the examined sample. With a temperature decrease the peak is narrowing and its intensity rises. The reason is the strengthening of charge carrier localization in the delta-layer region, expressed by square root temperature decreasing of Debye screening length L_D:

$$L_D = \left(\frac{\varepsilon\varepsilon_0 kT}{e^2 n}\right)^{1/2}. \qquad (1)$$

Here e is the electron charge and n is the free charge carrier concentration.

In our numerical model we took the delta layer width equal to 3 nm, and the bulk concentration within the layer was varied in the range 1×10^{17}–5×10^{19} cm^{-3}. As a whole, the presence of a delta layer does not affect the Fermi level position in a structure, because the contribution of the delta layer (or QW + delta-layer) is less than 0.1% of the sample's thick electrical neutrality part. The delta layer's impact is efficient only at distance of 1–3 Debye lengths. If a QW is placed within this distance, the delta layer acts as an efficient supplier of additional free charge carriers. In order to prove this conclusion we simulated the concentration profiles for a set of test structures with QW $In_{0.22}Ga_{0.78}As/GaAs$ of 10 nm width and a delta layer at various distances from the QW (Figure 5). The simulation showed that the separate peaks due to the QW and delta layers can be resolved in the concentration profiles (Figure 5a), when the distance between the QW and delta layer is not less than 20 nm (the energy band offset at the QW heterojunction is 175 meV). At decreasing distance between the QW and delta layer we observe a drop in the concentration peak from the delta layer and a rise in the peak from the QW, which is driven by charge carrier capture by the QW. The presence of a delta-doped layer also has an impact on the energy of confined levels in the QW (Figure 5b).

The results for the sample with a single QW $In_xGa_{1-x}As/GaAs$ (x = 0.22) and a delta-doped layer at various temperatures are presented in Figure 6.

On temperature decrease we observe the narrowing and intensity growth for peaks both from the QW and delta layer, similar to that observed for the structure with a single QW and the structure with a single carbon δ-layer. Against the above-mentioned structure with a single QW InGaAs/GaAs, for the structure with

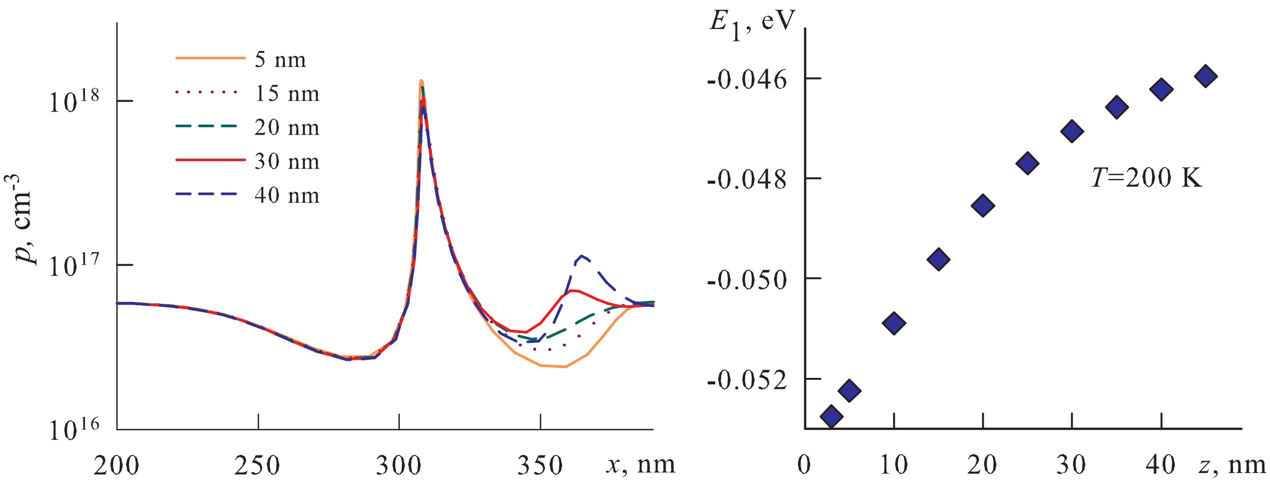

Figure 5. Simulated data for the sample with a single QW $In_xGa_{1-x}As/GaAs$ (x = 0.22) and a delta-doped layer: (a) modeling of apparent carrier concentration profile for various distances between QW and delta layer; (b) impact of distance between QW and delta layer (z) on quantum-confined level position E_1 (T = 200 K, QW width is 10 nm).

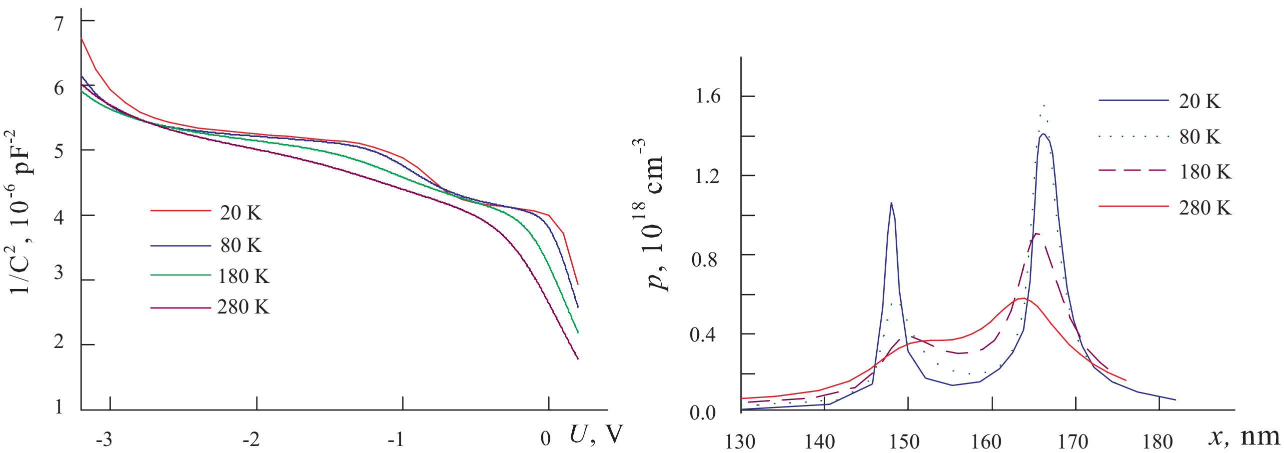

Figure 6. Capacitance investigations for the sample with a single QW $In_xGa_{1-x}As/GaAs$ (x = 0.22) and a delta-doped layer at various temperatures: (a) CV characteristics; (b) apparent concentration profiles of charge carriers (holes).

a QW and a delta-doped layer we observe weaker reduction of amplitude of the apparent charge carriers with temperature increase. This occurs due to the fact that the delta layer, located near the QW, acts as a carrier supplier for the QW. This weakens the temperature dependence of FCC concentration, since the temperature increase results in probability growth for both the thermal activation emission of carriers from the QW and the capture of carriers from the delta layer due to the reduced localization degree of charge carriers in the δ-layer region. Lowering of temperature leads to enhancement of this interaction.

4. Conclusions

In the present work a complex experimental and theoretical approach was applied to investigate heterostructures containing a QW and tightly positioned delta-doped layer. The performed theoretical investigations showed that at distance between the QW and delta layer of less than 3 Debye lengths, the delta layer plays a role as an efficient supplier of charge carriers to the QW region. The induction by delta-layer Coulomb potential in the QW region provokes a modification of wave functions and quantum levels' positions change.

The upgrading of the experimental ECV setup and using appropriate liquid electrolyte as a barrier enabled for the first time the observation of two peaks in apparent free carrier concentration profiles: from the QW and from the delta layer. The conducted work may help in improvement of SHF devices, allowing one to increase the gain coefficient and transconductance of transistors.

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