The control of electrophysical properties of GaAs pHEMT heterostructures

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Abstract. AlGaAs/InGaAs/GaAs pHEMT heterostructures were investigated by means of electrochemical capacitance-voltage (ECV) and photoluminescence (PL) techniques coupled with a numerical simulation. A set of GaAs pHEMT structures was fabricated using various doping techniques: modulated and δ-doping. The results of the PL spectra simulation and ECV free charge carrier distributions for investigated structures are presented. The analysis and comparison of QW filling in case of different doping mechanism of donor layer was done. Based on obtained results, we suggest optimized heterostructures in order to obtain higher electron localization and occupation of the quantum states.

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]. 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 reproducibility of the sequence, composition, and doping level of the layers. Therefore, the right choice and optimization of diagnostic techniques for such structures along with numerical simulation is an important and relevant task.

In present work we have investigated a set of pHEMT samples of various design based on GaAs, using several complementary methods: Hall measurements, electrochemical capacitance-voltage profiling [3] and photoluminescence measurements at various temperatures. Basing on self-consistent solution of Schrodinger and Poisson equations we calculated PL spectra [4] for investigated heterostructures and compared them with the experimental data.

The main goal of our investigation was to explain any possible deviations of the experiment data from the theoretical one and to study the features of free charge carriers spatial distribution in GaAs pHEMT heterostructures.
2. Samples and experimental technique

In this work we investigated three types of pHEMT heterostructures grown by the MBE (figure 4). Samples №1 and №2 had different type of donor layer (emitter): modulated (bulk) and δ- one. The asymmetrical Al0.22Ga0.78As/In0.22Ga0.78As/GaAs quantum well (QW) of these samples had 14 nm width and located at depth of 39 nm and 31.5 nm, respectively. In this case, sample №1 had a sufficiently thick donor layer. Sample №3 has two-side doping of 12 nm QW, which was located at a depth of 54.5 nm. Each donor layer had thin undoped Al0.22Ga0.78As spacer layers on both sides.

| Sample №1 | Sample №2 | Sample №3 |
|-----------|-----------|-----------|
| GaAs cap layer | GaAs cap layer | GaAs cap layer |
| Al0.7Ga0.3As stop layer | Al0.7Ga0.3As stop layer | Al0.7Ga0.3As stop layer |
| GaAs smoothing layer | GaAs smoothing layer | GaAs smoothing layer |
| Al0.22Ga0.78As donor layer | δ-Al0.22Ga0.78As donor layer | Al0.22Ga0.78As donor layer |
| In0.22Ga0.78As QW | In0.22Ga0.78As QW | In0.22Ga0.78As QW |
| GaAs buffer | GaAs buffer | GaAs buffer |
| GaAs S/I substrate | GaAs S/I substrate | GaAs S/I substrate |

Figure 1. The sequence of layers in investigated samples.

The ECV measurements were performed at room temperature using ECVPro (Nanometrics). A 0.1M Tiron solution was chosen as an electrolyte [5]. The area of the electrolytic rectifying contact was 0.1 cm², etching current was maintained at level of 0.5 mA/cm². During ECV profiling the samples were etched gradually with 1 nm step. The ac test signal frequency was 300 Hz. In some of experiments, the Agilent E4980A LCR-meter was used [6].

Photoluminescence spectra were measured at 77 K and 300 K using conventional synchronous detection with a lock-in selective amplifier, monochromator and photodetector. A solid-state single-mode laser module with a continuous output power of 40 mW at wavelength of 532 nm was used as an excitation light source. The laser beam was modulated and focused on a sample surface into a 100 microns diameter spot. Obtained signal was amplified by a selective nanovoltmometer and detected with a processing unit.

3. The experimental and simulation results and discussion

In this part of the paper both the experimental ECV results of measured free charge carriers depth distributions and PL spectra simulation results are presented.

3.1. ECV results

The apparent free charge carrier depth distribution profile of sample №1 with modulated doping of QW was measured at several measurement points (figure 2). As could be seen from the figure, the obtained ECV data shows 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 donor region, the second at a depth of 44 nm - response from the QW. The free charge carriers concentration of the donor layer is 1.5·10¹⁸ cm⁻³, the concentration in the QW is 2·10¹⁸ cm⁻³, which corresponds to a concentration of a 2DEG of 1.6·10¹² cm⁻². The results are well correlated with Hall measurements, the peaks position corresponds to the regions of charge carrier localization according to structure’s specification. A slight mismatch (less than 5 nm) with respect to the position of quantum well associated peak is observed, it is explained by QW skew [7]. It is important to note that the peak corresponding to the donor layer in such structures could be registered only by the ECV technique. According to the literature, conventional CV gives only one (attributed to QW) peak at the concentration profile [8]. It is shown in figure 3. The presence of two peaks is explained by the smaller Schottky barrier in case of electrolytic rectifying contact [9].
Figure 2. Apparent free charge carrier profile of sample №1 (modulated-doped GaAs pHEMT) measured in 4 different measurement points.

Figure 3. Available working range of conventional CV technique for GaAs pHEMT structures.

Figure 4. Apparent free charge carrier profile of sample №2 (δ-doped GaAs pHEMT) measured in 3 different measurement points.

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.
We investigated and analyzed the regularity of changing of the concentration peak associated with the quantum well of sample №3. The change in the amplitude is caused by a change of a QW filling degree due to the top layers etching. It is shown on figure 5. This feature is very useful on practice, since it could be used for controlled thinning of the HEMT gate region in order to saturate the QW with charge carriers, increase the channel conductivity and device operating current. For investigated HEMT structure design, the optimal value of thinning is 16 nm corresponding to the boundary of the smoothing and barrier (donor) layers. The estimated by ECV 2DEG density in QW is $2 \times 10^{12}$ cm$^{-2}$, according to Hall measurements this value was $2.14 \times 10^{12}$ cm$^{-2}$. Note that ECV etching is carried out only in a small region of 3 mm diameter, thereby simulating conditions of a real thinning technology of gate region.

![Figure 5. Apparent free charge carrier profiles of sample №3 obtained from a measured at each etch step CV plot. Inserted graph: dependence of QW filling from the etching depth.](image)

3.2. **PL simulation results**

GaAs has direct band gaps corresponding to the near-infrared region of the spectrum. This leads to highly informative optical measurements (primarily, photoluminescence spectra) of such pHEMT heterostructures, which can be effectively used for structure characterization along with electrical methods. PL is non-destructive and rapid technique of semiconductor structures analysis, widely used to determine grown layers composition, for evaluation heterostructure quality and many other parameters [11, 12].

For detailed analysis of the PL spectra of investigated structures we performed a numerical self-consistent solution of Schrodinger and Poisson equations. Stresses due to the structure pseudomorphic growth were taken into account using the deformation potentials theory and data introduced in [13].
Basing on the suggested theoretical model we calculated PL spectra for the heterostructures and compared them with the experimental data.

We assumed parabolic dispersion laws both in conduction and valence bands determined by electron and heavy hole effective masses:

\[ E_n(k) = E_n^0 + \frac{\hbar^2 (k^2_x + k^2_y)}{2m_e}, \quad (1) \]
\[ E_m(k) = E_m^0 - \frac{\hbar^2 (k^2_x + k^2_y)}{2m_h}, \quad (2) \]

where \( E \) - energy, \( k \) – wave vector, \( \hbar \) – Plank constant, \( m \) – effective mass.

In our theoretical model we have such expression for PL intensity:

\[ I(\hbar \omega) \sim \sum_{m,n,k,k'} |M_{mn}(k,k')|^2 \times \delta(\hbar \omega - (E_n(k') - E_m(k))) \times (1 - f(E_n(k), F_p)) \times f(E_n(k'), F_N) \quad (3) \]

where \( I \) – PL intensity, \( M \) – transition matrix element, \( f \) – probability density function, \( F \) – quasi Fermi level.

Matrix element is:

\[ M_{mn}(k,k') = \frac{1}{2} \langle m,k | \hat{H}_{\text{mat}} | n,k' \rangle, \quad (4) \]

\[ |M_{mn}(k,k')|^2 = |M_{mn}|^2 \delta_{kk'}. \quad (5) \]

where \( \hat{H} \) – Hamiltonian operator, \( \delta \) – Kronecker delta-function.

Probability density function is:

\[ f(E_n(k), F_p) = \frac{1}{1 + \exp\left(\frac{E_n(k) - F_p}{kT}\right)} \quad (6) \]

Taking into account (1), (2) and (4) - (5), the expression (3) for calculating the PL intensity may also be formatted as:

\[ I(\hbar \omega) \sim \sum_{m,n} |M_{mn}|^2 \Theta(\hbar \omega - (E_n - E_m)) \times \]

\[ \times \frac{1}{1 + \exp\left(\frac{E_n - \frac{m_e}{m_e + m_h} (\hbar \omega - E_n + E_m) - F_p}{kT}\right)} \times \frac{1}{1 + \exp\left(\frac{E_n - \frac{m_h}{m_e + m_h} (\hbar \omega - E_n + E_m) - F_N}{kT}\right)} \]

where \( \Theta \) - Heaviside step function:

\[ \Theta(\hbar \omega - (E_n - E_m)) = \frac{1}{1 + \exp\left(\frac{\hbar \omega - (E_n - E_m)}{\Gamma}\right)} \quad (8) \]

In our model we used following adjustable parameters: \( \Gamma \) – spreading parameter, \( F_p \) – holes quasi Fermi level, \( \Delta E_{\text{v}} \) – valence band offset. Conduction band offset was \( \Delta E_{\text{c}} = 0.85x - 0.3x^2 \).

The experimental and simulated PL spectra of structures similar to sample №1 is shown on figure 6. We observe two PL peaks with different intensity in the 1000 nm region. These peaks are formed due to recombination of electrons from the first and the second energy subbands in conduction band and holes in valence bands. It could be seen that the simulation results are in a good agreement with
the experimental data. The difference in PL spectra between these structures is explained by the different growth temperature of the QW layer. With a rise of growth temperature, increases segregation and diffusion of indium atoms, which leads to enlarge of the interface spreading. The reduction in QW width due to the indium segregation is accompanied by the long-wavelength peak predominance, which can be explained by a weak filling of the second energy subband in the relatively narrow QW. At the same time, the peak separation is less dependent on the growth parameters and stays about 40 nm.

Figure 7 shows experimental and simulated PL spectra (at various temperatures) of pHEMT structure with higher doping level of donor layer. With decrease of the temperature the spectrum thermal spreading also decreases, so we could observe two peaks in PL spectra. If we will compare PL spectra, shown in figure 6 and figure 7, we could conclude that the form of PL spectra is in a strong dependence of donor doping level.

![Figure 6](image6.png) **Figure 6.** The experimental (300K) and simulated PL spectra of GaAs pHEMT structures with a different QW growth temperature.

![Figure 7](image7.png) **Figure 7.** The experimental and simulated PL spectra (at various temperatures) of GaAs pHEMT structures with a highly-doped donor layer.

4. Conclusion

In this work a set of GaAs pHEMT heterostructures was investigated by means of ECV and PL techniques coupled with a numerical simulation. The apparent free charge carriers depth distribution profiles are obtained, the position of the donor layer and 2DEG concentration in the QW are estimated. The obtained results show high repeatability and well correlated with Hall measurements. The comparison of the apparent free charge carriers profiles of GaAs pHEMT structures with different types of donor layer doping (modulated and δ-) showed identical QW filling. Despite the apparent absence of δ-doping advantages, less thickness of top layers, allows to obtain a greater value of the steep subthreshold slope characteristic, and therefore ability of better control of the final device with the same operating current and power. This also helps reduce the cutoff bias. It was shown that by using the ECV technique one could optimize the etched thickness of a cap layers to obtain the best concentration of free charge carriers in QW of a pHEMT device and to enlarge it’s operating current. The comparison of experimental and simulated PL spectra established the dependencies of PL peaks shape, position and intensity on the structure properties, primarily donor doping level. These dependencies may ideally point out the deviation of grown structure from the standard one.

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