The built-in electric field in P-HEMT heterostructures with near-surface quantum wells \( \text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Ga}_{1-y}\text{As}/\text{GaAs} \)

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Abstract

This study is concerned with the built-in electric field of heterostructures with the quantum wells grown at different depths \( L_b \) with respect to the surface. All samples had the same concentration of the two-dimensional electron in the quantum wells \( \text{AlGaAs/InGaAs/GaAs} \). The built-in electric field was determined from the photoreflectance spectra of the samples. In case of \( L_b \) decreasing, the intensity ratio of two peaks in the photoluminescence spectra increases. The calculation shows that occurred effect originates from the redistribution of doping atom and variation of the surface potential due to the fact that the quantum well is set closer to the surface.

1. Introduction

Field-effect transistors with a two-dimensional (2D) high-mobility and high-density electron gas are extensively used for production of present-day devices in microwave electronics. At present, \( \text{AlGaAs/InGaAs/GaAs} \) pseudomorphic high-electron-mobility transistor (P-HEMT) nanoheterostructures, in which the mobility \( \mu \) and the concentration \( n_s \) of electrons in the 2D electron gas are higher than the corresponding parameters in the \( \text{AlGaAs/GaAs} \) heterostructures, are widely used for development of advanced microwave electronic devices [1,2].

In the \( \text{Al}_x\text{Ga}_{1-x}\text{As} \) alloy, the Fermi level is pinned at surface states with a large capacitance near the midgap. Because of this, a rather high built-in electric field is produced in the depletion region between the surface and the quantum well (QW) filled with electrons. As the QW with the 2D electron gas is approved closer and closer to the surface, the effect of the built-in electric field in the heterostructure becomes more and more pronounced, which influences the electrical and optical properties of such structures. Therefore, consideration of these factors is of great importance in the development of advanced transistor heterostructures [3].

In this study, we investigate the built-in electric field of heterostructures with the quantum wells grown at different depths \( L_b \) with respect to the surface using a specially developed approximation. In this approximation, the total concentration of electrons in the subbands of the QW remains unchanged when the QW is set closer to the surface.
2. Experimental

The samples were grown at Institute of Ultra High Frequency Semiconductor Electronics by molecular-beam epitaxy on semiinsulating GaAs (100) substrates 2” in diameter. The structure of the samples corresponds to the standard of P-HEMT structure with one side δ-doping [4]. The width of the InGaAs QW was 11 nm in all of the samples. The barrier layer thickness $L_b$ was 18, 15, 13, 11 and 9 nm in samples #1, 2, 3, 4 and 5, respectively. Such barrier layer thicknesses are the typical values used in the production of low-noise microwave transistors. The molar fractions of components in the ternary $\text{Al}_x\text{Ga}_{1-x}\text{As}$ and $\text{In}_y\text{Ga}_{1-y}\text{As}$ compounds corresponded to $x = 0.23$ and $y = 0.20$ for all of the grown samples. The concentration of 2D electrons were determined from Hall measurements. The measurements were accomplished for mesa structures shaped as Hall bridges. The photoluminescence (PL) spectra were recorded by the standard method [4]. The photoreflectance (PR) spectra were registered by 0.3 m double grating monochromator equipped with Si photodiode in the spectral range of 550 – 1100 nm. The pitch angle of the probe beam was equal to 8°. The modulation of reflectance was made by irradiation of LED (maximum wavelength 540 nm) flashed at 370 Hz. All experiments were carried out at room temperature. The detailed description of the experimental technique is scribed in [5].

3. Results and discussion

By self-consistently solving the set of the Schrödinger and Poisson equation, we calculated and analyzed the spatial profile of the conduction band edge $U(z)$, the electron energy levels $E_i$, the envelope wave functions of electrons in subbands $\psi_i(z)$, the distribution of the electron density $n(z)$ at different barrier layer thickness, and the concentration of donors $N_d$. For a certain level of doping, the calculations showed that, as barrier layer thickness $L_b$ is increased, the size-quantization levels $E_i$ shift to lower energies, thus leading to increase of the difference $E_F – E_i$. We calculated the compensating increase in the degree of doping of the Si-doped δ layer at smaller $L_b$ and, thus, determined the increase, necessary for keeping the constant concentration of electrons in the QW. The results of the calculations are shown in figure 1. With regard to these results, we grew five MBE samples with close concentrations of the 2D electron gas in the QW. The samples differed in barrier layer thickness ($L_b = 18, 15, 13, 11$ and 9 nm) and degree of doping $N_d = (4.3, 5, 5.7, 6.6$ and $8.25) \times 10^{12}$ cm$^{-2}$. The experimental data determined from Hall measurements showed that in all of the five samples concentrations of 2D electrons are very close to each other: $n_H = (1.54–1.77) \times 10^{12}$ cm$^{-2}$. Some of the parameters of the samples are listed in the table 1. The PR spectra of investigated samples are shown at figure 2. There are four spectral peculiarities in the spectra: with energies less than 1.4 eV is connected with the interband transitions in the InGaAs quantum well, in the spectral range of 1.4-1.5 eV is connected with the fundamental transitions in the GaAs layer, in the spectral range of 1.6-1.8 eV is connected with the interband transitions in the AlGaAs/GaAs buffer superlattice and

| Samp. # | $L_b$, nm | $n_H$, ×10$^{12}$ cm$^{-2}$ | $E$, kV/cm |
|---------|------------|-----------------------------|------------|
| 1       | 18         | 1.54                        | 350        |
| 2       | 15         | 1.69                        | 523        |
| 3       | 13         | 1.70                        | 613        |
| 4       | 11         | 1.71                        | 752        |
| 5       | 9          | 1.77                        | 890        |

Table 1. Sample parameters. $L_b$ is barrier thickness, $n_H$ - Hall concentration at 300 K, $E$ - built-in electric field determined from theory and PR spectra
Figure 1. Isolines corresponding to constant concentrations of electrons in the QW. Isolines 1, 2 and 3 correspond to the concentrations (1.7, 1.4 and 1.1)×10^{12} cm^{-2}. The dashed line indicates the concentration chosen for the experimental series of samples – 1.6×10^{12} cm^{-2}.

in the spectral range of 1.8-2.3 eV is connected with the fundamental transition in the δ-doped Al_{x}Ga_{1-x}As barrier layer. The electric field strength \( E \) in the delta-doped Al_{x}Ga_{1-x}As barrier layer was calculated from the results of linear regression in accordance with the Aspnes model [6] and have been shown at the table 1.

The PL spectra of the samples exhibited two bands, at the photon energies \( \hbar\omega_1 = 1.28–1.30 \) and \( \hbar\omega_2 = 1.35–1.38 \) eV. These bands are identified as defined by transitions from the first and second electron subbands to the first subband of heavy holes, \( e1–h1 \) and \( e2–h1 \), respectively. The PL spectra shown in figure 3 are typical for the samples where the Fermi level is located between the first \( (E_0) \) and the second \( (E_1) \) size-quantization subbands (figure 4). In addition, as \( L_b \) decreases, the intensity of the peak corresponding to the transitions \( e2–h1 \) increases. Changes in the rate of optical transitions are commonly related to two factors. The one is the change in the matrix elements of transitions and the breakage of the selection rules under changes in the built-in electric field. This factor is associated with the symmetry of the QW, since the overlapping of the wave functions of electrons and holes depend on the built-in electric field. The other factor is the change in the relation between the concentrations of electrons in the subbands of the QW. In other studies, a change in the spectrum was observed if the Fermi energy and the concentration of electrons in the QW were

Figure 3. PL spectra of samples #1, #3, #5 at 77 K.

Figure 4. The potential profiles of the conduction band \( U_c \) for samples #1 and #5. The profiles are reduced to one point \( \Delta z \) corresponding to the boundry of the QW.
increased and the upper size-quantization band $E_i$ was filled with electrons. The two above factors always “worked” in combination.

In this study, the total concentration of electrons and the position of the Fermi level in the QW were chosen to be constant and the built-in electric field and the symmetry of the QW were varied only because of variations in the potential profile in the AlGaAs barrier layer and the δ-layer with donors. As the calculations of the band structure showed, the rate of the transitions $e_2$–$h_1$ increases with decreasing $L_b$, since the built-in electric field increases as the QW approaches the surface. A decrease in $L_b$ yields an increase in the energy of the conduction band in the QW region, resulting in a decrease in the concentration of the 2D electron gas in the QW. To keep the constant concentration of electrons in the QW, we increased the strength of the built-in electric field in the AlGaAs barrier region by increasing the concentration of donors in the Si δ-layer. As the calculations of the changes in the band structure in figure 4, the potential profiles of the conduction band in the samples were shifted with respect to each other to have one common point, the upper boundary of the QW. In this case, the coordinates of the surface $\Delta z$ of different samples do not coincide, but the surface potential $\phi_s = 0.7$ eV is the same for all of the samples.

The electrostatic dipole interaction between carriers localized in surface states and their parent donors causes the donor to segregate along with the growing surface. Thus, when the QW is set closer to the surface, spatial profile of the doping increases. In addition, when $L_b$ decreases, the surface potential $\phi_s$ decreases as well. The above effects for #5 are showed on the figure 4 by dash line. In this case, the curvature of the bottom of the conduction band in the QW is enhanced. As the curvature of the bottom of the QW increases, the overlapping of the wave functions of electrons $e_2$ and holes $h_1$ becomes more efficient, resulting in an increase in the intensity of the PL peak corresponding to the transitions $e_2$–$h_1$. Thus, the experimentally observed changes in the positions of the PL peaks and the change in the rate of the transitions $e_2$–$h_1$ should be attributed to the change in the doping profile and variation of the surface potential.

4. Conclusion

In this study, the built-in electric field of heterostructures with the quantum wells grown at different depths $L_b$ with respect to the surface is analyzed. The effect of variations of the AlGaAs barrier layer thickness $L_b$ and of Si-doping level on the energy band spectrum is simulated. To keep the concentration of electrons in the QW constant, we increase the strength of the built-in electric field in the AlGaAs barrier region by increasing the concentration of donors in the Si δ-layer. As the parameter $L_b$ is decreased, variations in the potential profiles of the conduction band occur in the regions of the $V$-shaped potential of the δ-layer and QW. Comparison of determination the built-in electric field from PR spectra and the band structure calculations shows that altering in the intensity ratio of two peaks in the PL spectra originates from the redistribution of doping atoms and variation of the surface potential.

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