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Abstract. A comparison of the electron transport properties of pseudomorphic quantum well $Al_xGa_{1-x}As/In_{0.2}Ga_{0.8}As/GaAs$ with those of conventional donor layer (x=0.15 and x=0.25) and with AlAs nanoinserts around the delta-Si layer or AlAs: delta-Si donor layer is presented. The structures with added AlAs layers exhibit electron concentration decrease, combined with increased electron mobility. This effect is related to the suppression of remote ionized impurity electron scattering, change of band structure and decreasing efficiency of silicon atoms doping when incorporating in pure AlAs.

1. Introduction

Due to high electron velocity and two-dimensional electron gas density, pseudomorphic high electron mobility transistors (PHEMT) are one of the most widely used materials for microwave semiconductor electronics. Increasing electron mobility while a high electron concentration is maintained is still an important challenge. Delta doping through the spacer layer allows high electron concentration, yet remote ionized impurity scattering becomes a significant factor, as it vastly decreases electron mobility. Also, some portion of conduction electrons begin to move in the region of the doping layer [1]. Thus, parallel conduction appears in two layers: in the $_xGa_{1-x}As$ quantum well layer with high electron mobility and the wide-bandgap barrier layer with low mobility [2-4]. This second parallel conducting channel leads to nonlinear transistor gate characteristics and increasing noise [5]. This parasitic effect can be avoided by using two-sided doping or by increasing the height of the $Al_xGa_{1-x}As$ barrier due to a larger AlAs mole fraction. The first drawback is that the wide-bandgap AlGaAs layer in HEMT heterostructures can increase ohmic contact resistivity between drain and source. The second is that the properties of $Al_xGa_{1-x}As$ become ineligible due to the increase of ionization energy and reduction of doping efficiency if AlAs content is high enough. DX-centers appear at x>20%, leading to [6, 7]. However, in contrast to bulk layers, the position of the donor level energy can be influenced by the electrostatic potential distribution in heterostructure. The ionization of deep levels can be high enough if they are located considerably higher than Fermi level in heterostructures if the donor layer is located close to the quantum well. Some papers show increased electron mobility in AlGaAs/GaAs HEMT with AlAs spacer and barrier layer [8]. Thus, the problem of eliminating parallel conduction without using thick AlGaAs barrier layers with increased AlAs content is of great importance.

In this paper, we study the electron properties of PHEMT quantum wells with two types of barrier/donor layer: one containing AlAs nanoinserts around the delta doping layer and another with

AlAs:δ-Si doping layer. A comparison with standard PHEMT structures with a smooth $Al_xGa_{1-x}As$ barrier with different Al mole fraction is carried out (x=0.15 and x=0.25).

2. Samples growth and preparation

A series of PHEMT samples with one-sided silicon delta doping was grown using molecular-beam epitaxy on semi-insulating GaAs (100) substrates. To improve buffer quality, an AlGaAs/GaAs superlattice was grown on the substrate. GaAs buffer layer is also a barrier for the $In_{0.2}Ga_{0.8}As$ quantum well from one side. From the other side, the $Al_xGa_{1-x}As$ layer serves as a barrier and spacer with aluminium mole fraction x = 0.16 for samples 1-3 and x = 0.25 for samples 4 and 5. The distance between the quantum well and delta-layer was 8 nm for samples 1-3 and 5 nm for samples 4 and 5. After the delta-layer $Al_xGa_{1-x}As$, a Schottky barrier was grown: 26 nm wide for samples 1-3 and 20 nm for samples 4 and 5. The top of the heterostructure was capped with a slightly doped 13 nm GaAs layer. In sample 2, the delta-layer was surrounded by two 1 nm-wide AlAs nanolayers separated by 4.2 nm. In sample 3, an 8 nm layer AlAs with the delta-layer in the middle was grown at the distance of 4 nm from the quantum well heterojunction.

For transport measurements, Hall-bar mesa structures were made using photolithography and wet etching, with Ni/AuGe/Ni/Au ohmic contacts, which were annealed at 390 °C [9]. Electron mobility and concentration measurements were carried out at magnetic fields up to 6 $kgs^{-2}A^{-1}$ in a temperature interval of 2.1 K ÷ 300 K with a Cryo-free 404 system.

3. Band structure and electron states modeling

The band structure, the potential profile, the energies of subbands and the profiles of the electron wave functions were calculated for samples 1, 2 and 3. Due to heavy doping in sample 1, the conduction band potential around the delta-layer is decreasing, which leads to the change in the wave functions profile: the ground state wave function ψ_1 is mainly localized in the quantum well, yet partially permeates into the barrier. Wave functions of excited states become hybrid: ψ_2 and ψ_3 has the same amplitude around donors and in the quantum well. In this case, electrons in these subbands have low mobility because of ionized impurity scattering. Moreover, these subbands are close in energy ($E_3 - E_2 \leq 15$ meV) and thus the wave functions ψ_2 and ψ_3 have a large spatial overlap. The addition of two thin AlAs barriers around the Si delta-layer significantly changes the shape of the wave functions and the energies of the upper subbands. The AlAs inserts do not noticeably change the energy of the ground state; however, the amplitude of wave function ψ_1 around the donors is 4.5 times lower in the second sample and 200 times lower in the third sample. The excited states ψ_2 and ψ_3 are mostly localized in separate parts of the structure – ψ_2 inside the quantum well, while ψ_3 is predominantly around the delta-layer. The reason for these changes is that adding AlAs nanobarriers mainly increases electron state energy around the donor delta-layer. At the same time, the energy gap $E_3 - E_1$ is increased by 20 meV and the ψ_2 and ψ_3 states overlap is greatly reduced. Confinement increase in the quantum well for the state ψ_2 also leads to a slight increment in the intersubband gap $E_2 - E_1$ by ~ 14 meV.

In sample 3, an 8 nm AlAs layer greatly increases the energy of the bottom of the conduction band around the region of donors, thus forcing out electron states from the donors region. As Figure 1 shows, in that case the wave functions of the first and second subband become almost completely confined in the InGaAs quantum well.

With increasing barrier height caused by adding AlAs, the difference between first and second subband energies increases, and the bottom energy of conduction band around the delta-layer does not influence them because these two subbands are associated with the quantum well. Energy of the third subband, associated with the delta layer, increases by 20 meV with the addition of AlAs inserts around the donor layer and considerably more so in the case of an AlAs donor layer.

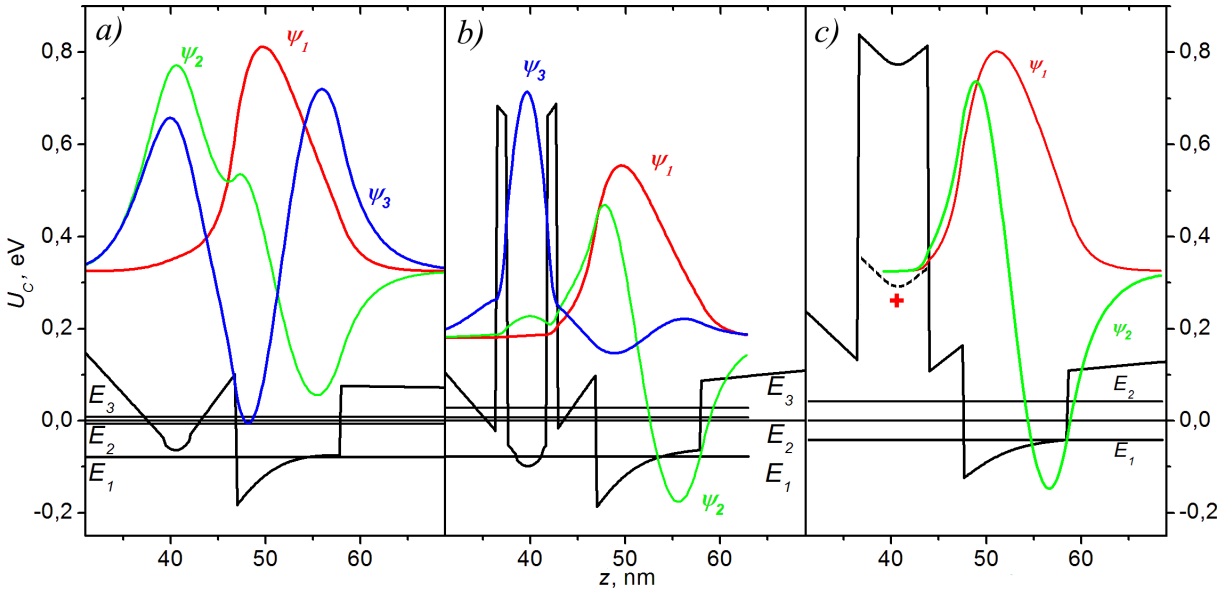

Figure 1. Conduction band profile and electron wavefunctions in PHEMT quantum wells, from left to right: a) conventional structure, b) structure with the two AlAs nanolayers surrounding δ-Si area, c) structure with the AlAs:δ-Si donor layer.

Furthermore, band structure around the donor delta-layer affects the donor ionization energy. With adding AlAs nanobarriers, Si donor states, that in hydrogen-like approximation have an effective width of wave function of about 5 nm, suffer a level shifting proportionate to the increase of average Al mole fraction x in the wide-gap barrier layer. In case of a solid AlAs(Si) layer in sample 3, the ionization donor energy decreases relatively to the conduction band bottom, however the donor level turns out to be higher than the conduction band bottom in the surrounding ternary layer AlGaAs and about ~ 260 meV higher than Fermi level.

4. Results and discussion

Specific resistance of samples, Hall mobility and concentration of electrons were measured in the temperature range from 2.1 K to 300 K. Electron mobility increases with decreasing temperature, and along the whole range of measurements, the third sample has the highest mobility.

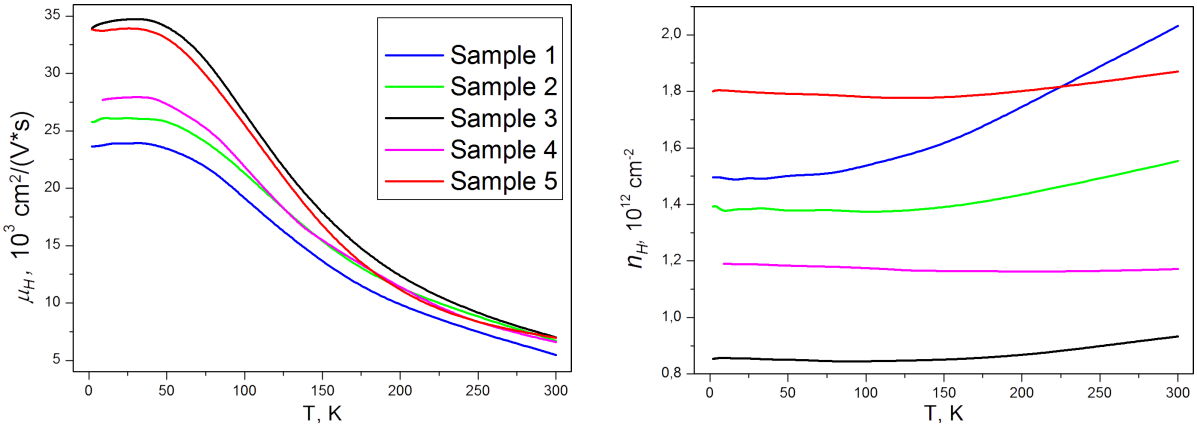

Figure 2. Temperature dependencies of electron mobility (left) and Hall concentration (right) in the samples.

The AlAs mole fraction in the barrier layer $Al_{0.16}Ga_{0.84}As$ of samples 1 and 2 was chosen to be comparatively small, so as to keep ionization donor energy sufficiently low relative to the edge of conduction band. On the other hand, conduction band energy in the barrier turns out to be small. On the contrary, in samples 4 and 5, AlAs content is high, which provides higher conduction band energy in the barrier.

In sample 1, electron concentration temperature dependence shows the largest increase at temperatures T > 100 K.

Adding two AlAs barriers slightly decreases Hall concentration, while temperature dependence becomes weaker. An even fainter change of electron concentration is observed in samples 4 and 5, despite the fact that sample 5 has the greatest value of electron concentration.

This can be explained by the fact that the ionization effectiveness of Si donors depends on the position of donor levels relatively to Fermi level, which in turn depends on both aluminum content in $Al_xGa_{1-x}As$ and donor concentration. Adding nanobarriers surrounding Si delta-layer increases donor ionization energy level since Bohr radius for ionized impurity of Si in the hydrogen-like model is an order of about ~ 10 nm [10], so in sample 2, donor level rises relative to the edge of the conduction band. Donor ionization is better at low temperatures; electron concentration growth begins at higher temperature and has a lesser value. Nevertheless, despites identical doping of samples 1 and 2, sample 2 with AlAs nanoinserts shows less electron concentration value. Also, in sample 3 with the AlAs donor layer, donor impurity concentration was 1.3 times higher; however, Hall electron concentration turned out to be ~ 2 times less than in sample 1. Band structure calculation shows that in the AlAs donor layer, the impurity level associated with X-valley is located ~ 0.52 eV lower than the G-valley conduction band bottom, and in the case of sample 3 is ~ 300 meV higher than Fermi level. So in such a way, the decrease of the electron concentration effect in the discussed PHEMT heterostructures is not related to ionization since Si donor level is located high enough, however with the decrease of silicon incorporation, effectiveness as donor impurity with increasing AlAs content. Besides, since donor level in AlAs is associated with X-valley and the effective mass of X-electrons is substantially larger than G-electrons, effective wave function width of the donor state turns out to be 4 times less. Thus, impurity ionization energy in the delta-doped AlAs nanolayer must correspond to its value in bulk AlAs. This explains the donor ionization peculiarity of increasing temperature in different samples: in sample 1, $n(T)$ has maximum growth, whereas in sample 2, concentration change is less and the temperature of change-over to increasing dependence is higher. In sample 3, increasing $n(T)$ turns out to be the weakest. Similar behavior of concentration temperature dependence shows samples 4 and 5 with uniform barrier layer with higher AlAs content.

Hall electron mobility behavior differs in samples 1-3 and 4, 5. With increase of silicon donors concentration by 2.1 times in sample 5 in comparison with sample 4, Hall concentration increases by ~ 1.5 times. According to data obtained from band structure modeling and Shubnikov-de Haas effect analysis, in samples 4 and 5 with a higher aluminum mole fraction, only one subband is populated. At the same time, due to better screening and increase in Fermi-momentum electron mobility is also increasing with electron concentration. A different situation is observed in samples 1-3. Electron mobility in these samples is increasing with decreasing Hall concentration. This can be explained with the decrease of remote ionized impurity electron scattering due to suppression of electrons tunneling from the quantum well to wideband barrier. Also, the electron mobility changes with the addition of AlAs is related to the population of higher subbands in samples 1 and 2. In sample 2, the electron concentration in the second subband is about 2% of the concentration in the first subband. In sample 1, where mobility is the lowest, electron concentration in the second subband is 10% of the first one. In sample 3, which has the highest mobility, the second subband population is neglected because of lower Si doping efficiency in AlAs. Thus, mobility in samples 1-3 increases with the addition of AlAs layers in the barrier because electrons localize predominantly in the ground subband with the highest electron mobility.

5. Conclusion

A comparison of electron transport properties of the pseudomorphic quantum well $Al_xGa_{1-x}As/In_{0.2}Ga_{0.8}As/GaAs$ with a conventional donor layer (x=0.15 and x=0.25) and with AlAs nanoinserts around the delta-Si layer or the AlAs doped barrier layer is presented. Structures with AlAs layers show an increase of electron mobility combined with slightly decreased electron concentration. This effect is related to the suppression of remote ionized impurity electron scattering, change of band structure and decreasing efficiency of silicon atom doping in pure AlAs.

Acknowledgments

The research was supported by the State assignment program № 8.3887.2017/PCH.

References

[1] Vasil'evskii, I S, Galiev G B, Klimov E A, Mokerov V G, Shirokov S S, Imamov R M and Subbotin I A 2008 *Semiconductors* **42** 9
[2] Van der Burgt M, Karavolas V C, Peeters F M, Singleton J, Nicholas R J, Herlach F, Harris J J, Van Hove M and Borghs G 1995 *Phys. Rev. B.* **52** 16
[3] Lisesivdin S B, Yildiz A, Balkan N, Kasap M, Ozcelik S and Ozbay E 2010 *J. Appl. Phys.* **108**
[4] Masselink W T, Braslau N, Wang W I and Wright S L 1987 *Appl. Phys. Lett.* **51** 19
[5] Chen Y W, Hsu W C, Shieh H M, Chen Y J, Lin Y S, Li Y J and Wang T B 2002 *IEEE Trans. Elec. Dev.* **49** 2 pp 221-225
[6] Schubert E F and Ploog K 1984 *Phys. Rev. B.* **30** 12
[7] Godts, P, Constant E, Depreeuw D, Zimmerman J and Danneville F 1988 *Electr. Lett.* **24** 15
[8] Holland M C, Skuras E, Davies J H, Larkin I A, Long A R and Stanley C R 1995 *J. Cryst.Growth* **150**
[9] Vanyukhin K D, Zakharchenko R V, Kargin N I, Pashkov M V and Seidman L A 2015 *Russian Microelectronics* **44** 8 pp 122-127
[10] Bastard G 1990 *Wave mechanics applied to semiconductor heterostructures*.