Effect of thin heterogeneous functional nanolayers on electron transport in InGaAs-based quantum wells with high electron density (a review)

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Abstract. A prospective improvement of InGaAs-based quantum well heterostructures design is possible towards the quantum treatment of electron subbands states and electron transport processes in the real structures with thin spatially inhomogeneous functional nanolayers. Insertion of nanosized GaAs, AlAs and InAs layers into quantum well/spacer/barrier layers or applying a graded InₓGa₁₋ₓAs channel can enhance electron transport properties and gives a novel degree of freedom for the quantum structures engineering. The review and original study for PHEMT/GaAs, HFET/GaAs and InP HEMT structures are discussed.

1. Introduction

Compound semiconductor heterostructures become widely last thirty years and provided a unique functionality and performance due to the quantum engineering. Among the most important application the field effect transistors based on high electron mobility transistor (HEMT) structures became a fundamental for microwave nanoelectronics [1]. Unless InGaAs quantum well HEMT structures still dominate in the compound semiconductors for microwave monolithic integrated circuits (MMIC), the insight in electron transport processes in such structures aren’t so deep as for well elaborated “classical” AlGaAs/GaAs HEMT. Researchers sought rather to benefit from these structures for the microwave applications than to go deeper in fundamental electron processes. In particularly it is reflected in empirical approach for the set of physical relations, for example velocity-field, bandgap-temperature and others. Since initial stage of detailed study of AlGaAs/GaAs HEMT left away and condensed matter theoreticians attention moved to the spin related phenomena and strong correlated systems, leaving a lot of questions for the detailed insight. The practical heterostructure design turned to deeper InGaAs- based quantum well structures with different InAs content that usually have a higher concentration of two-dimensional electron gas. Electron transport peculiarities in such structures haven’t been investigated in details. InGaAs based quantum wells have a different basic types dependent on InAs composition and substrate type: AlGaAs/InGaAs pseudomorphic HEMT (PHEMT, ~20% InAs), lattice matched to InP InAlAs/InGaAs HEMT (53% InAs) and pseudomorphic QW HEMT on InP (60-80% InAs) [2]. The structures also differ by dopant arrangement (one side or double side delta-doping) and nowadays steady trend of double-side doping strategy appears. Power performance along with cutoff frequency increase in HEMT application require the further development of widely used InGaAs channel HEMTs [3] while GaN based structures are still more expensive and technologically tough.
Another apparent trend towards the increase of MMIC operation frequency is the increase of InAs composition in QW channel. Heterostructure design follows the three dimensional scaling, because one should bring the channel closer to the surface to maintain electrostatic control together with the decrease of gate length.

Due to the surface potential and high charge density in modern HEMT structures band profile is affected by strong electric field. In turn it causes the changes both electron confinement and subband structure at low electric field and real space transfer of hot carriers [3, 4]. Complicated quantum effects as state hybridization can take place [5].

Additional degree of freedom for quantum well HEMT structures engineering gives a composite functional nanolayers such as composite quantum well, spacer and barrier layers. The major importance for such structures must be paid for multiple subband electron transport, effective mass engineering and self-consistent electron wavefunction spatial profiles.

The present paper gives the state-of-the art overview of different InAs content structures with functional nanolayer insertions and spatially inhomogeneous layers in PHM ET and HFET AI, Ga, As/In, Ga, As/Al, Ga, As on GaAs, HEMT and PHM ET In, Al, As/In, Ga, As/In, Al, As on InP. The considered approaches employ either binary AlAs and GaAs inserts or ternary In, Ga, As, and Al, Ga, As layers with compositional gradient.

2. Composite spacer with AlAs nanoinserts for high density 2DEG in HEMT and PHM ET quantum well structures

High doping through a spacer usually applied to obtain high density of two dimensional electron gas in HEMT quantum wells. Resulting charge separation produces dipole electrical field that lowers the conduction band energy around the doped wideband barrier and also bends a quantum well profile. This negative effect on the one hand reduces quantum well effective depth and for the other, gives rise to tunnel penetration of electron wavefunction from QW to the barrier. Interaction of electron states is manifested in subband energy level anticrossing with increasing spacer thickness accompanied by electron mobility crossing [6]. As this effect has tunnel origin, an insertion of 2 nm AlAs barrier in AlGaAs spacer can effectively destroy the tunnel states’ coupling and separates electron mobility to higher one for QW-confined state and lower one associated with V-shaped potential well of ionized donors. For the shallow Al, Ga, As/GaAs:δ-Si donor layer causes substantial energy shift for the electron states associated with V-potential well in the QW barrier and completely crowds out electron density from the barrier. Temperature dependence of electron sheet concentration n, showed a decreased temperature variation due to an increase of donor ionization energy level by such insertions. For 1δ-PHEM T Al, Ga, As/In, Ga, As/GaAs quantum well δ-Si doped GaAs donor layer was applied, as shallow Si ionization energy provides very high electron concentration. However, introduction of double AlAs nanolayers around δ-Si:GaAs sufficiently decreases temperature sensitivity of Hall electron concentration from 37% to 12% and enhances electron mobility in the sample. Low temperature magnetotransport data for the two samples 261 and 262 with simple spacer and with composite spacer containing double 2 nm AlAs insertions around δ-Si layer depicted in Figure 1 a) and b), correspondingly. It can be seen that for composite spacer structure 262 magnetoresistance demonstrates approximately constant monotonic component and Shubnikov-de Haas oscillation started at a smaller magnetic field. For the sample 261 magnetoresistance monotonic component is positive and quadratic that is typical for multiple subband occupation. This indicates that in composite spacer sample electron states considered in [7] are moved away from delta-doped layers and electron mobility in ground subband in QW is increased. Fourier analysis of SdH oscillation determined electron density in QW ground subband. Analysis showed a slight increase of electron density in QW for sample 262 and the absence of a parallel conduction, whereas for sample 261 electron density in QW accounted as only 65% at high temperatures. Sample
262 has $n_s=1.55 \times 10^{12} \text{ cm}^{-2}$ and $\mu_H = 6720 \text{ cm}^2/(\text{V s})$ and $\mu_H = 25770$ at $T=300 \text{ K}$ and $T=4.2 \text{ K}$, respectively.

Figure 1. Magnetoresistance and Hall effect in high magnetic field at $T=4.2 \text{ K}$ for PHEMT QW with simple spacers (a) and composite spacers containing double AlAs insertions (b).

Thin directly $\delta$-Si doped AlAs donor layer in PHEMT $\text{Al}_{0.24}\text{Ga}_{0.76}\text{As}/\text{In}_{0.2}\text{Ga}_{0.8}\text{As}/\text{GaAs}$ QW showed mobility enhancement up to $\mu_H = 30000 \text{ cm}^2/(\text{V s})$ and $33000 \text{ cm}^2/(\text{V s})$ at $T=77 \text{ K}$ and $T=4.2 \text{ K}$, respectively [8], that are comparable values for InP HEMT structures. On the other hand, doping efficiency are shown to be 3-4 times smaller in comparison to GaAs so donor concentration must be sufficiently increased in AlAs donor layers to provide $n_s \approx 1.5 \times 10^{12} \text{ cm}^{-2}$.

AlAs thin barriers grown in QW spacers allow also to avoid a real space transfer of hot electrons the towards wideband barriers in high electric field, that is rather important for microwave transistors. Another approach presented in papers [3, 9] for DA-PHEMTs utilize an engineering of built-in electric field by combination of donor and acceptor compact doping. In this case tunneling from QW to wideband AlGaAs barrier are suppressed by high electrostatic potential in acceptor layers. Substantial increase of transistor gain has been reported in DA-PHEMTs compared with ordinary PHEMT structure [3].

3. Doped GaAs nanolayers for extremely high density 2DEG in HFET quantum well structures

For power applications heterostructure field effect transistor structures (HFET) are used with directly doped channel. This eliminate any parallel conduction and allow one to increase AlAs content in the Schottky barrier as high as 30-35% to depress a leakage current and provide large modulation of gate signal [10]. On the contrary this structure layout breaks the principle of modulation doping and towards the electron concentration in the range $n_s \approx 3 \times 5 \times 10^{12} \text{ cm}^{-2}$ HFET structures demonstrate very low electron mobility $\mu_H \approx 1500 \text{ cm}^2/(\text{V s})$. A compromise approach was presented in our previous work [11] by the compound channel structure $\text{Al}_{0.38}\text{Ga}_{0.62}\text{As}/\text{In}_{0.15}\text{Ga}_{0.85}\text{As}/\text{Al}_{0.38}\text{Ga}_{0.62}\text{As}$ with additional 9 nm GaAs sublayers that served as sub-barriers at the QW heterointerfaces. Redistribution of Si doping from the uniform doped QW to delta-doping in two GaAs nanobarrriers have been studied and an enhancement of QW conductivity and electron mobility have been found. Effect is explained by suppression of electron amplitudes at the sub-barrier area and decrease of ionized impurity direct electron scattering when the dopants are partially placed aside of channel center. A combination of $n_s = 1.37 \times 10^{13} \text{ cm}^{-2}$ and $\mu_H = 1520 \text{ cm}^2/(\text{V s})$ have been obtained in such structure.

4. Compositonally graded PHEMT quantum wells

For the double-side $\delta$-Si doped 2D-PHEMTs $\text{Al}_x\text{Ga}_{1-x}\text{As}/\text{In}_x\text{Ga}_{1-x}\text{As}/\text{Al}_x\text{Ga}_{1-x}\text{As}$ an increase of doping concentration allows to obtain $n_s \approx 3 \times 5 \times 10^{12} \text{ cm}^{-2}$ but accompanied by a decreased electron mobility. One of the reasons is the decrease of effective QW depth due to rise of parabolic electrostatic potential barrier at the QW center. This barrier deforms electron wavefunction (WF) by moving electron density
towards the heterointerfaces. The other reason for decreased $\mu$ is shrinking energy difference between the ground and first excited subband. As a result, electron density in the ground subband saturated with increasing dopant concentration. This unwanted effect can be compensated by deliberate growth of graded composition layer $\text{In}_y\text{Ga}_{1-y}\text{As}$ taking into account $E_g(y)$ dependence. This approach has been realized by MBE with relatively slow growth rate and very high compositional gradient up to 2%/nm to compensate linear (for $1\delta$-PHEMTs) and parabolic (for $2\delta$-PHEMTs) band bending at QW [12]. For the one-side doped PHEMTs such a grading of quantum well bottom doesn't vary electron subband energies but moves the centroid of 2DEG towards the QW center. For $2\delta$-PHEMTs effective QW depth (which can be defined as energy separation between ground electronic subband and the minimum for barrier potential) increased in the QW with elevated InAs content in the center, even though mean InAs content in $\text{In}_y\text{Ga}_{1-y}\text{As}$ layer remained. The structure with optimal InAs profile that produced most rectangular profile shown to have both a highest mobility and conductivity (latter is increased by 25% compared with the standard structure).

5. Composite quantum wells with InAs single and multiple inserts

Increase of InAs composition in $\text{In}_{0.52}\text{Al}_{0.48}\text{As/In}_y\text{Ga}_{1-y}\text{As/In}_{0.52}\text{Al}_{0.48}\text{As}$ HEMT structures grown on InP substrates realized by the two approaches. First is to growth pseudomorphically strained QW with uniform InAs composition ($0.53<y<0.8$), however, even for $y=0.8$ substantial thickness limitation due to strain restricts QW thickness to less than 10 nm. The second technique is compound quantum well (CQW) with additional InAs sub-channel. These structures have demonstrated great performance for short channel microwave transistors and circuits [13, 14]. Nevertheless, such structures aren’t deliberately explored from the quantum states and electron transport peculiarities, concerning e.g. negative effects of CQW thickness shrinkage, comparison of CQW with the different numbers of InAs inserts. For single InAs insert it is known that WF of ground state grows at the insert place and leads to CQW effective thickness shrinkage. Accordingly to the tunnel effect we have supposed that multiple InAs inserts could conserve relatively wide composite QW. Self-consistent calculation for single QW and composite CQW, containing one, two and three InAs inserts has been performed. Conduction band and electron wavefunctions profiles are presented in Fig 2 for single QW, two and three 2 nm InAs inserts CQW. It can be seen that double InAs inserts slightly modulate the profile of ground state wavefunction, whereas tree inserts CQW demonstrates the shift of 2DEG centroid towards the upper heterointerface. Thus right CQW with 3 inserts edge substantially shifts upward and WF amplitude at the third insertion becomes rather small. This indicates that 3-insertion CQW isn’t effective, but 2-insertion CQW is quite attractive. Energy levels in the CQW with different InAs total thickness have been calculated and shown on Fig. 3. Three models are presented - single $\text{InAlAs/InAs/InAlAs}$ QW, and $\text{InAlAs/InGaAs/InAlAs}$ - based CQW with one and two InAs inserts.

![Figure 2. IR-transmission spectra of experimental samples (a). The result of decomposition of the absorption spectrum for the sample deposited at 800°C (b).](image)

To account for the band structure effects on electron transport properties, electron mobility calculation have been performed for interface roughness scattering mechanism. The mobility
dependence on InAs total thickness is shown in Fig. 4. It can be seen that for the interval \( L_{\text{ins}} = 1 \div 4 \) nm the highest \( \mu \) corresponds to the double insertion CQW, and single deep InAs QW demonstrates a lower \( \mu \). The main reason is that the different quantum structures have the different energy level variation due to insertion thickness deviation. The determined dependence of \( \partial E/\partial L_{\text{ins}} \) on \( L_{\text{ins}} \) has the form \( \partial E/\partial L_{\text{ins}} \sim L_{\text{ins}}^{-k} \) where \( k \approx 2.4 \) for SQW, \( k \approx 1.0 \) for the one-insertion CQW and \( k \approx 0.6 \) for the double insertion CQW. Note that for infinitely deep QW the exponent should be \( k \approx 3 \). This implies that for double insertion CQW quantum well has a large effective thickness and less sensitive to individual insert roughness. Also for the double insertion CQW energy difference between the two lower subbands remains nearly constant in the practical range of \( 1 \text{ nm} < L_{\text{ins}} < 5 \text{ nm} \), indicating that electron states are not localized at individual inserts in contrast to the case of a single insertion CQW.

![Graph](image)

**Figure 3.** IR-transmission spectra of experimental samples (a). The result of decomposition of the absorption spectrum for the sample deposited at 800°C (b).

Experimental for the two InAs insertion CQW have shown indeed some decrease of electron low field mobility [15], probably because lateral roughness and mechanical deformation distribution played an additional important role in CQW crystalline perfection and scattering processes. However in high electric field clear dependence of high field mobility and electron velocity and also saturation field value have been reported depending on either one or two InAs insertion presence and GaAs subbarriers at the CQW edges. The main reasons of such effects are effective mass tuning and also optical phonon modes selection by an insertions [16, 17], as it was predicted by numerous works devoted to optical phonon confinement and scattering form-factor adjustment by thin heterogeneous layers [18, 19]. Thus InAs and GaAs nanized insertions rather than AlAs wideband inserts served as electron-phonon scattering tuning barriers, because AlAs too much outrages electron subband structure being introduced in QW area.

**6. Conclusion**

A number of new approaches that using spatially inhomogeneous functional nanolayers in InGaAs channel-based HEMT quantum wells are discussed in the context of the influence on electron states, quantum treatment of electron scattering processes. Insertion of nanized GaAs, AlAs and InAs layers into basic functional layers as quantum well/spacer/barrier or applying a graded \( \text{In}_y\text{Ga}_{1-y}\text{As} \) channel can enhance electron transport properties and gives a novel degree of freedom for the quantum structures engineering.

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