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Pseudomorphic HEMT quantum well AlGaAs/InGaAs/GaAs with AlAs:δ-Si donor layer

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Abstract. A comparison between the electron transport and optical properties of pseudomorphic high electron mobility quantum well with conventional AlGaAs donor layer and with AlAs delta-Si doped donor layer is presented. The structure with AlAs donor layer exhibits a mobility rise combined with the electron concentration decrease. We address this effect to the suppression of electron scattering on remote donor impurities and the decreased doping efficiency of Si atoms embedded in pure AlAs.

1. Introduction

Pseudomorphic quantum well heterostructure with high electron mobility is the most widely used material for microwave compound semiconductor electronics. The advantages of PHEMT are high electron velocity and density, high enough breakdown electric field and excellent manufacturability. The best performance of the monolithic microwave integrated circuits devices based on PHEMT technology are shown for X, Ku and Ka bands [1-3]. PHEMT technology benefit is low-noise amplifiers and other related MMICs. Despite layout variety of PHEMTs the common features for this type of structure are AlAs content in the barrier and Schottky layers in the range of 0.15÷0.25 and InAs content in the quantum well (channel) in the range of 0.15÷0.25. Typical electron transport properties of PHEMTs are electron concentration in the range $(1\div3)\cdot10^{12}$ cm^{-2} and electron mobility in the range 5000÷6500 $cm^2/(V\cdot s)$ at room temperature [4,5]. The choice of InAs content in the $In_yGa_{1-y}As$ ternary is ruled by the compromise between the quantum well depth and electron effective mass on the one hand and the elastic lattice deformation limit for the strained $In_yGa_{1-y}As$ layer on the other. The reason of AlAs content in $Al_xGa_{1-x}As$ is different and related to the compromise between the barrier height and electron trapping in $Al_xGa_{1-x}As$:Si layer due to DX-centers for the $x > 0,25$ [6,7]. DX centers also can affect the transistor performance by the interaction of hot carriers [8]. AlAs also rarely used because of its low stability to atmosphere ambient. It used even as etch stop layer in some cases to achieve certain recess depth [9]. Some study revealed the enhanced electron mobility in AlGaAs/GaAs HEMTs with AlAs spacer and barrier [10]. High electron mobility and low scattering are essential for low noise application. So the attempts to enhance of electron mobility at room temperatures for PHEMTs are useful. AlAs/GaAs heterojunction has significant conduction band discontinuity for Γ-band electrons and AlAs has X-band minima itself. DX-center energy as ~30 meV above X-minima was reported [11] so it corresponds to ~ 12 meV below the Γ-band and thus no trapping effect expected for the heterostructure with AlAs donor layer.

We have investigated the PHEMT quantum well structure electron properties with nonuniform QW barrier, containing AlAs:δ-Si doped donor layer in comparison with the conventional PHEMT with uniform AlGaAs barrier.

2. Electron band structure

The conduction band profile and the subband structure were calculated for PHEMTs with conventional AlGaAs donor layer (left) and with AlAs delta-Si doped donor layer (right) by solving the Schrödinger and Poisson equations self consistently for the electrons in Γ-band. The δ-doped layer had a nominal width of 3 nm. The conduction band profiles shown in Fig.1, zero energy corresponds to Fermi level.

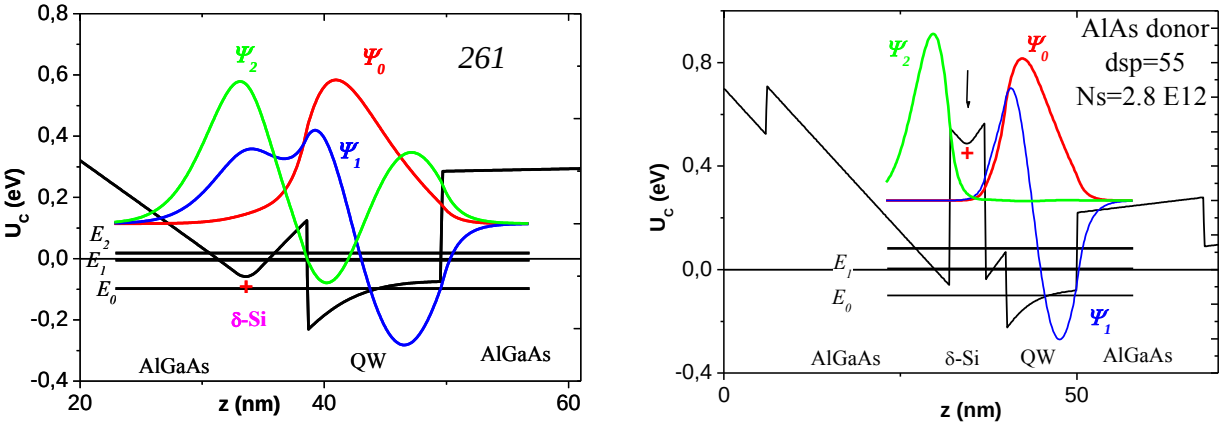

Figure 1. Conduction band U_c and electron wave functions profiles, subband energy levels for PHEMTs with conventional AlGaAs donor layer (left) and with AlAs delta-Si doped donor layer (right).

Conduction band profile is modified by AlAs: δ-Si barrier and U_c increased considerably around the Si donor area. Thus Si donor level in AlAs must be substantially above Fermi level, whereas for the conventional uniform AlGaAs barrier it can be near or even below E_F. In [12] Si activation energy in bulk Si doped AlAs is 57 meV, but should decrease in delta-doped layer due to very high donor density.

It can be seen from Fig.1 that the introduction of AlAs: δ-Si as donor layer changes the electron subband energies and wavefunction spatial profiles. For the ground state subband the confinement in the channel area increases without a remarkable shift in subband energy E_o. As for the excited states, in the uniform barrier-donor AlGaAs the Ψ_1 and Ψ_2 wavefunctions are hybridized towards the extended area of V-shaped potential well around Si donors and InGaAs channel. AlAs donor serves as high potential barrier thus suppressing a tunnel coupling between InGaAs channel and the low-energy triangle well to the left side of AlAs. Thereby the second subband E_1 wavefunction becomes completely confined in InGaAs QW. The third subband shift is most valuable and its energy increases by ~75 meV.

3. Sample growth and preparation

Pseudomorphic $In_{0.2}Ga_{0.8}As$ quantum well structures with uniform $Al_{0.24}Ga_{0.76}As$ donor layer (sample 261) and with AlAs delta-Si doped donor layer (sample 24B) were grown by molecular-beam epitaxy on semi-insulating (001) GaAs substrates. Quantum well width L_{QW} was 10 nm. The samples were delta doped by Si from the upper side through 5.5 nm spacer with concentrations of $3.2 \cdot 10^{12}$ cm^{-2} for the sample 261 and 1.33 times higher for the sample 24B. The last has 6 nm AlAs with delta-Si doping at the center keeping the same delta-layer position related to QW as in the sample 261.

For the electron transport measurements samples were processed by photolithography and mesa etching followed by the AuGe/Ni contact metallization and rapid thermal annealing at 390 °C. Hall bar lateral probe distance were 3.5 times of channel width.

4. Results and discussion

4.1. Electron transport properties

Electron transport properties were measured at the different temperatures in the range 4.2 K to 295 K. Both samples demonstrate the metallic behavior of the sheet resistance. Electron mobility rises while the temperature is decreased, but the mobility is higher in the sample 24B. The parameters are listed in Table 1.

Table 1. Electron transport properties of the samples at the different temperatures.

Sample #	Donor layer	295 K		77 K		4.2 K	
		nH, 10^{12} cm^{-2}	μH, cm^2/Vs	nH, 10^{12} cm^{-2}	μH, cm^2/Vs	nH, 10^{12} cm^{-2}	μH, cm^2/Vs
261	Standard	1.55	7 160	1.23	28 500		
24B	**6 nm AlAs: δ Si**	0.94	**7 320**	0.83	**30 470**	0.83	**33 150**

Despite the increased doping level in the sample 24B it demonstrates the decreased by ~ 2.2 times Hall electron concentration compared to the standard sample 261. Nevertheless the concentration variation with the temperature decrease shown to be lower in for the sample with doped AlAs. The reduced electron concentration in QW with doped AlAs can be addressed by low efficiency of Si atoms incorporation in Al sites of AlAs during the doping. Despite the decreased electron density in QW their mobility is sufficiently higher and reaches the values that are typical for the InP HEMT quantum well structures. We attribute this effect to the suppression of electron scattering on remote ionized donor impurities through the tunneling depression of the QW ground state wavefunction through the AlGaAs barrier. It is worth notice that the energies of the two lowest quantum state in the structures mainly refer to the quantum well and are weakly dependent on the conduction band energy at the donor area. Thus the observed change of mobility isn't connected to any intersubband scattering effects.

4.2. Photoluminescence spectroscopy

The photoluminescence (PL) spectra of the samples have been measured at T = 77 K. The results are reported in Fig. 2.

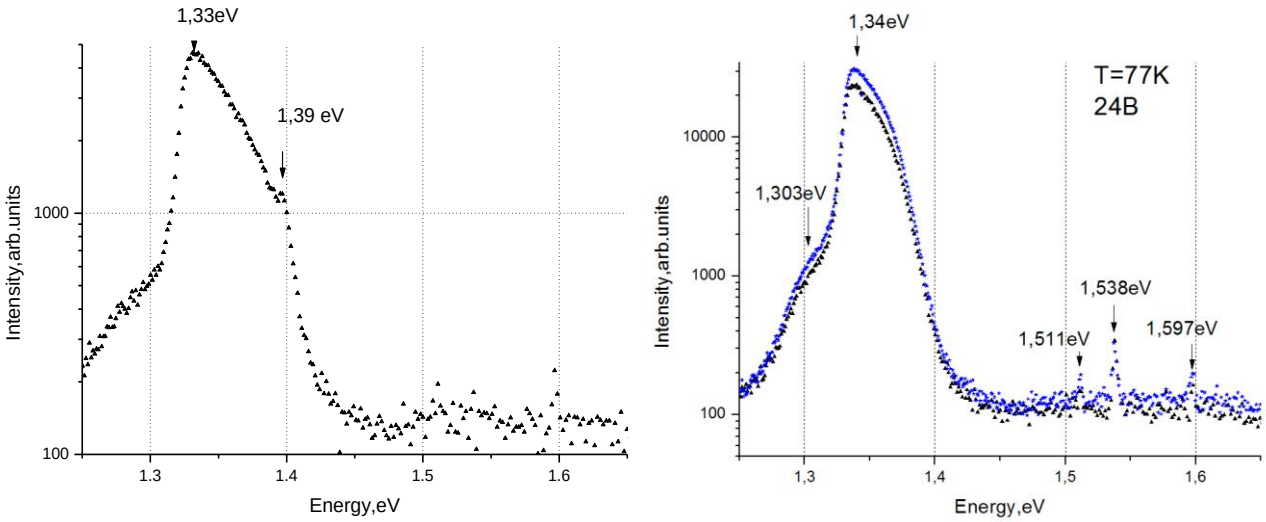

Figure 2. Photoluminescence spectra of PHEMTs with conventional AlGaAs donor layer (left) and with AlAs delta-Si doped donor layer (right) at T = 77 K.

All PL spectra of the $In_{0.12}Ga_{0.88}As$ quantum wells exhibit a pronounced maximum in the energy range 1.30÷1.40 eV, which is somewhat below the transition in bulk GaAs at 1.508 eV. For the PHEMTs with conventional AlGaAs donor layer (left) and with AlAs delta-Si doped donor layer (right) the peaks are relatively broad and the PL intensity rise differs for the different sample, indicating the presence of several transition energies. For a sample with PHEMTs with AlAs donor layer the PL peak is less broad, which shows that the upper electron levels are unoccupied. Furthermore, one can see a significant enhancement of PL intensity for the sample 24B. It can originate from the enhanced confinement of photoinduced carriers in the QW area.

5. Conclusion

A comparison between the electron transport and optical properties of pseudomorphic high electron mobility quantum well with conventional AlGaAs donor layer (left) and with AlAs delta-Si doped donor layer is presented. The structure with AlAs donor layer exhibits a mobility rise combined with the electron concentration decrease. We address this effect to the suppression of electron scattering on remote donor impurities and the reduced doping efficiency of Si atoms embedded in pure AlAs.
Photoluminescence spectroscopy shows the decrease of main peak width in the sample with Si-doped AlAs donor layer and the significant enhancement of PL intensity.

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