Influence of silicon donor doping on electron transport in quantum wells AlGaAs/InGaAs/GaAs at different temperatures

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Abstract. Electron transport in single delta-Si doped pseudomorphic quantum wells with increasing donor concentration analyzed in a temperature range 2–300K. Hall effect and Shubnikov-de Haas oscillations studied at low temperatures. Temperature dependences of electron sheet concentration differ: samples with higher doping show significant increase of electron concentration at high temperature, while for the lightly doped it has a minor temperature sensitivity due to the band peculiarities of donor ionization. Electron mobility increases and then decreases at higher electron concentration, although the second quantum well subband remains unpopulated.

1. Introduction
Unlike well-elaborated “classical” high electron mobility heterostructures (HEMT) based on AlGaAs/GaAs quantum well (QW), application-related approach dominates for pseudomorphic structures (PHEMT) with InGaAs QW channel rather than fundamental approach for study of electron processes at high electron density \( n_S > 1.5 \times 10^{12} \text{ cm}^{-2} \). State-of-the art analysis shows an ambiguity of electron mobility dependence on doping concentration in PHEMT quantum wells AlGaAs/InGaAs/GaAs [1-3]. In different papers authors are interpreting either increasing or decreasing behavior of electron mobility with increase of electron concentration in terms of remote ionized impurity scattering mechanism. Thus behavior of \( \mu(n) \) dependence in PHEMT quantum wells within the wide range of donor concentration haven’t a common physical explanation, so the optimization of electrical conductivity and scattering processes in such QW heterostructures is still of great importance.

In PHEMT structures electron concentration can be increased by applying higher donor doping concentration and by double-side doping strategy. Usually in typical pseudomorphic quantum wells second QW subband becomes populated at electron concentration values about \( n_s > 2 \times 10^{12} \text{ cm}^{-2} \) [4], and Coulomb interaction effects lead to significant disturbance of the conduction band profile in the structure. This, in turn, changes electron states’ spatial structure and electron scattering conditions. Spacer arrangement also strongly effects the mobility both in HEMT quantum wells and as well in the resonant tunneling structures with electron transport transversal to the structure layers [5].

2. Samples growth and preparation
To study the electron transport peculiarities a series of PHEMT \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{As/In}_{0.2}\text{Ga}_{0.8}\text{As/GaAs} \) samples was grown on semi-insulating GaAs (100) substrates by Riber Compact 21 molecular beam epitaxy. All samples had one-side delta doping with donor concentration \( N_D \) values in wide range from...
1.64⋅10^{12} \text{ cm}^{-2} \text{ to } 15.8⋅10^{12} \text{ cm}^{-2}. \text{ For electron transport measurements a Hall-bar mesa structures were made using photolithography and wet etching, with Ni/AuGe/Ni/Au ohmic contacts, annealed at 390 °C. Electron mobility and concentration measurements were carried out at magnetic fields up to 6 T in temperature interval of 2.1 K \div 300 K with Cryo-free 404 system.}

3. Results and discussion

Increasing silicon doping time in delta layer leads to increase of electron Hall concentration $n_H$ in the structure (fig 1, a). At small $N_D$ values charge carriers concentration in quantum well increases sharply, but at high donor concentration $n_H(N_D)$ dopind efficiency is reduced by ≈ 10 times, as it can be seen from the incline change of $n_H(N_D)$ dependence in Fig. 1a. For the further doping increase $n_H$ is weakly increases, despite of increasing N_D by more than 3 times. This might be caused by either worsening of silicon donors ionization efficiency with incomplete incorporating into metallic sites in the lattice or with band-related effects of interplay of donor energy and Fermi level position.

**Figure 1.** Hall electron concentration (a) and mobility (b) dependences on silicon concentration in delta layer in PHEMT QW samples.

Band profile modelling have shown that increasing of doping impurity concentration in one-side doped PHEMT quantum well of 10.5 nm width formed a quasi-triangular profile of quantum well bottom as a result of appearing strong electric field. Unlike the double side doped PHEMT structures, any considerable population of a second electron subband in QW for the single-doped QWs under study expected only at electron concentration $n_s > 2.7⋅10^{12} \text{ cm}^{-2}$.

All samples have been prepared to Hall bar geometry with low resistance alloying contacts [6]. In all samples at low temperatures Shubnikov-de Haas oscillations are observed. Only one oscillation frequency is present in all the samples matching the only populated lower subband in quantum well. Electron concentration in this subband was determined with fast Fourier transform of $\rho_{xx}(1/B)$ dependence and showed a good compliance with hall electron concentration. Besides, one can detect the multiple subbands population by nonlinearity of Hall resistance $\rho_{xy}(B)$. In studied samples $\rho_{xy}(B)$ remained linear even at high temperatures for all the samples, which also indicated the population of only one subband in QW. Thus the decrease of electron mobility with increasing electron concentration in quantum well (figure 1, b) does not related to population of the upper electronic subbands. At relatively low concentration values ($n_s < 1.5⋅10^{12} \text{ cm}^{-2}$) electron mobility increases as a result of Fermi-momentum increasing and screening improvement. Then, with further increase of doping mobility decreases because of switching to large angle electron scattering by ionized impurities. This mechanism is caused by an increase of tunnel transparence of wideband Al_{x}Ga_{1-x}As QW barrier for electrons in the ground QW subband due to lowering of conduction band energy with increased silicon donor concentration [5].
Electron mobility shows monotonic decrease with temperature increasing in all considered temperature range (figure 2, a), the most substantial reduction is observed at $T > 60$ K due to optical phonon scattering mechanism. Temperature dependence of electron mobility character is the same in all samples.

![Figure 2. Temperature dependencies of electron mobility (a) and Hall concentration (b) in the PHEMT samples with the lowest and highest Si doping concentration.](image)

Temperature dependencies of Hall electron concentration have a complicated character and differ in various samples (figure 2, b): in samples with moderate doping $n_{hi}$ is weakly changed in a whole temperature range. But in the samples with high $N_D > 3 \cdot 10^{12}$ cm$^{-2}$ a significant $n_{hi}$ increase is observed at higher temperatures. Switching to increasing dependence $n_{hi}(T)$ has different magnitude and takes place at the different temperatures. In sample with lower doping concentration increase of $n_{hi}(T)$ started at $T \sim 200$ K and has only 2% change of initial value. For the samples with higher doping turn to increasing of $n_{hi}(T)$ dependence occurs at the lower temperatures, and an increase of concentration $n_{hi}$ becomes more pronounced, reaching 15% in the sample with the highest doping.

This distinction is explained by donor ionization temperature dependence with lowering of conduction band bottom potential around delta layer. At lesser doping time ($n_{hi} < 2 \cdot 10^{12}$ cm$^{-2}$) donor level is located considerably higher than Fermi level and donor activation is high enough and weakly dependent on temperature. With increasing donor concentration conduction band potential at the delta layer begin to lower. In highly doped structures Si: AlGaAs DX-center level is located close to Fermi level and donor ionization is noticeably reduced and became temperature dependent. Temperature of switching to increase of $n_{hi}(T)$ dependence is decreased at higher doping concentration that implies the donor level approaching to Fermi level.

4. Conclusion

PHEMT band profile features define Hall electron concentration temperature dependence: at low doping concentration $n_{hi}(T)$ changes slightly while at high donor concentration $n_{hi}(T)$ increases from the some temperature value, that is decreasing with increasing donor concentration. This phenomena is linked to changes of electrons thermal activation from silicon donor stated with lowering of conduction band bottom potential.

Unlike double side doping, in studied single side delta-doped PHEMT only one subband is populated in the wide range of dopant concentration due to extended asymmetry of quantum well profile driven by high built-in electric field.

Nonmonotonic electron mobility dependence on Hall concentration is observed. Electron mobility increases with increasing donor concentration because of Fermi-momentum increasing. The mobility turns to decrease at the high dopand density because of tunnel penetration enhancement of wideband Al$_x$Ga$_{1-x}$As barrier for electrons in the quantum well with conduction band energy lowering.
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