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The deformation-potential scattering and alloy disorder scattering in donor-acceptor pHEMT heterostructures

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Abstract. The increase in the indium mole fraction in the quantum well of pHEMT heterostructures with donor-acceptor doping causes an increase in the 2DEG concentration from $2.2 \cdot 10^{12} \text{ cm}^{-2}$ to $3.9 \cdot 10^{12} \text{ cm}^{-2}$ and a decrease in mobility from $7900 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ to $7500 \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ at room temperature. The temperature dependencies of 2DEG mobility show that the deformation potential scattering grows at increment of indium mole fraction in quantum well. Absolute values of the deformation potential are approximately two times smaller than the widely used values and increases with increasing of indium mole fraction.

1. Introduction

In pHEMT heterostructures with donor-acceptor doping (DA-pHEMT) the density of two-dimensional electron gas (2DEG) grows sufficiently up to $(4 \div 5) \cdot 10^{12} \text{ cm}^{-2}$ without appearance of parasitic parallel conductance due to increase of the depth of quantum well (QW) [1]. In the case of a high 2DEG density, two or more subbands in QW are filled. It is known that the interaction between electrons and phonons changes when more than one subband in QW is filled, for example, in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ QW the dominant mechanism of electron energy relaxation on the deformation mode of acoustic phonons is replaced by the piezoelectric mode of acoustic phonons; piezoelectric constants differ for each subband [2].

In this paper the scatterings on acoustic phonons and alloy disorder in DA-pHEMT heterostructures with two filled subbands are investigated for the first time. At low temperatures in DA-pHEMT heterostructures the influence of scattering on polar optical phonons can be neglected. In this case the 2DEG mobility is limited by scattering on ionized impurity in δ -layers and acceptor p^+ -layers, deformational potential scattering and alloy disorder scattering [3]. Only deformational potential scattering depends on temperature among the mentioned above scattering mechanisms. Therefore, for the investigation of electron-phonon interaction the temperature dependencies of 2DEG mobility were measured in the range $6 \div 77 \text{ K}$. To study the alloy disorder scattering the mole fraction of indium in QW was varied in the range $0 \div 0.18$.



2. Details of experiments and 2DEG mobility calculations

The DA-pHEMT heterostructures were grown by molecular-beam epitaxy using a Compact 21T machine on (001) GaAs substrate. The buffer of heterostructures comprises 0.4 micrometer-thick GaAs layer and twelve-periods of GaAs/AlAs superlattice. The growth rate was 0.28 nm s^{-1} at the temperature 620°C and 0.24 nm s^{-1} at the temperature $500\text{--}520^\circ\text{C}$ for (Al)GaAs layers and InGaAs layers, correspondingly. The growth of δ -layers was carried out at the temperature 530°C . The layer consequence for DA-pHEMT heterostructures is shown in Figure 1 (without top n^+ -GaAs contact layer). The nearest to QW δ -layers (filling δ -layers) supplies electrons in QW. The donor concentration in the remote from QW δ -layers was close to the net acceptor concentration for the best compensation. Four samples were grown with the mole fraction of In, $y_{\text{In}}=0, 0.06, 0.12$ and 0.18 , respectively. The concentrations of donors (silicon) in δ -layers and acceptors (beryllium) were the same in all samples (see Figure 1).

The density and mobility of 2DEG were determined by Hall measurements at fixed magnetic field of 0.2 T . In case of DA-pHEMT heterostructures this method does not give errors [1]. The $\langle 00\bar{1} \rangle$ -oriented Hall bars with sizes $50 \times 300 \text{ }\mu\text{m}^2$ were prepared by photolithography method. The Ge/Au/Ni/Au ohmic contacts were formed by electron-beam evaporation and 5-min annealing in hydrogen atmosphere at 420°C . The samples were mounted at holder with moveable permanent magnet and put down into liquid helium dewar for the measurement of 2DEG mobility at different temperatures.

The 2DEG mobility calculations were performed by using the theoretical model described in our previous paper [3]. The scattering on ionized donors and acceptors, the scattering on deformation potential and alloy-disorder scattering were taken into account. We assumed that the Gaussian distribution with standard deviation $\sigma = 2.5 \text{ nm}$ describes the profile of δ -layers. The necessary for 2DEG mobility calculations the heterostructure band diagrams and subband wave functions $\varphi(z)$ were determined using the self-consistent Schrodinger-Poisson solver NextNano.

3. Results and discussion

The obtained values of 2DEG density and mobility at 290 K and 77 K are listed in Table 1.

Table 1. The values of 2DEG density and mobility.

y_{In}	290 K		77 K	
	$n, 10^{12} \text{ cm}^{-2}$	$\mu, \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$	$n, 10^{12} \text{ cm}^{-2}$	$\mu, \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$
0	2.16	7870	2.14	33700
0.06	2.90	7600	2.76	28400
0.12	3.36	7710	3.24	31200
0.18	3.91	7460	3.89	23900

It is seen from the Table 1 that the 2DEG density increases with the increase in the mole fraction of indium in QW. As follow from Table 1 and Figure 1, only for $y_{\text{In}}=0.18$ all donors in the nearest to QW δ -layers are ionized. The 2DEG mobility decreases when y_{In} increments at room and liquid nitrogen temperatures. Unlike to 2DEG density, the mobility changes non-monotonously with y_{In} increase. Such an increase in both the 2DEG density and the degree of ionization is explained by deepening of QW and by the lowering of subband levels relative to Fermi level.

The temperature dependencies of 2DEG mobility are shown in Figure 2. As one can see from this figure, the mobility has linear dependence on temperature at $T < 68 \text{ K}$ and it decreases more rapidly for higher temperatures. Such complicated dependencies can be explained by the influence of scattering on polar optical phonons. The mobility μ_{POP} limited by scattering on polar optical phonons with frequency ω depends on temperature as $\exp(-\hbar\omega/k_B T)$. One can estimate μ_{POP} by extrapolating of

linear mobility dependencies to temperature 77 K and using Mattheissen rule. It was obtained that the μ_{POP} values reduce from $1\,200\,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ for $y_{\text{In}}=0$ to $446\,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ for $y_{\text{In}}=0.18$. These values very well compare with the estimation $\mu_{\text{pop}} = 620\,000 \div 540\,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ for $y_{\text{In}}=0.165$ from paper [3].

The temperature dependence of 2DEG mobility in DA-pHEMT heterostructures at low temperatures ($T < 68\text{ K}$) can be described by the expression:

$$\frac{1}{\mu(T)} = \frac{1}{A \cdot T^{-1}} + \frac{1}{\mu_{\text{const}}}, \quad (1)$$

where $A \cdot T^{-1}$ describes the contribution from scattering on deformation mode of acoustic phonons, and μ_{const} – the summary contribution of alloy disorder scattering and ionized impurity scattering. The constants A and μ_{const} were found by the approximation of experimental data by the expression (1) with help of least square method. The approximation results are shown in Figure 2 by lines.

AlGaAs	6 nm
AlGaAs:Be doped	8 nm, $5 \cdot 10^{18}\text{ cm}^{-3}$
AlGaAs	7 nm
4 ML GaAs: δ_{Si}	$N_{\delta 1}, 4 \cdot 10^{12}\text{ cm}^{-2}$
SL AlAs/GaAs spacer	2 nm
4 ML GaAs: δ_{Si}	$N_{\delta 2}, 2 \cdot 10^{12}\text{ cm}^{-2}$
SL AlAs/GaAs spacer	3 nm
GaAs smoother	1.5 nm
In_yGaAs	14 nm, $y=0 - 0.18$
GaAs smoother	3 nm
SL AlAs/GaAs spacer	3 nm
4 ML GaAs: δ_{Si}	$N_{\delta 3}, 3 \cdot 10^{12}\text{ cm}^{-2}$
SL AlAs/GaAs spacer	2 nm
4 ML GaAs: δ_{Si}	$N_{\delta 4}, 3.8 \cdot 10^{12}\text{ cm}^{-2}$
AlGaAs	5 nm
AlGaAs:Be	15 nm, $2.5 \cdot 10^{18}\text{ cm}^{-3}$
Buffer layers/GaAs substrate	

Figure 1. The layers sequence and doping levels of the DA-pHEMT heterostructure.

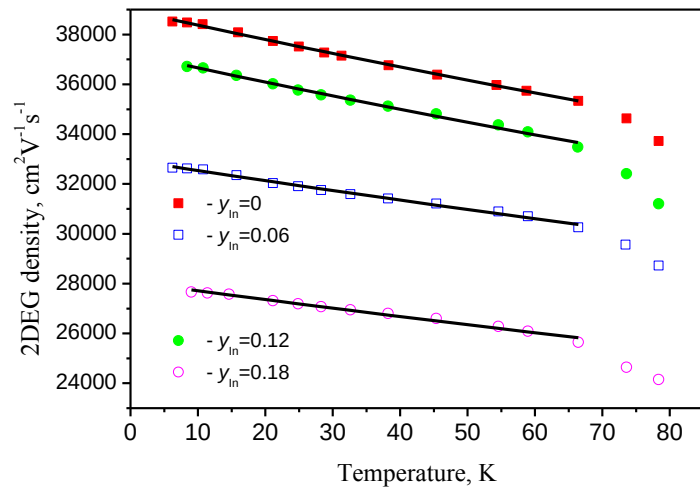


Figure 2. The temperature dependence of 2DEG mobility. Symbols denote the experimental data, lines show the results of approximation.

The obtained values of fitting parameters are listed in Table 2.

Table 2. The values of fitting parameters.

y_{In}	Parameters	
	$A, \text{K} \cdot \text{cm}^2\text{V}^{-1}\text{s}^{-1}$	$\mu_{\text{const}}, \text{cm}^2\text{V}^{-1}\text{s}^{-1}$
0	$2.51 \cdot 10^7$	38970
0.06	$2.57 \cdot 10^7$	32960
0.12	$2.32 \cdot 10^7$	37250
0.18	$2.14 \cdot 10^7$	28080

It is seen from the Table 2, the scattering on deformation potential raises at increment of y_{In} . The 2DEG mobility μ_{DP} limited by this scattering mechanisms at 77 K goes down from $326\,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ for $y_{\text{In}}=0$ to $278\,000\text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ for $y_{\text{In}}=0.18$. The last value in two and half times more than calculated

for $y_{In}=0.165$ in paper [3]. Therefore, the μ_{DP} in paper [3] is underestimated due to wrong choice of deformation potential.

The constant A is inversely proportional to square of deformational potential D [3]. Therefore, the dependence D on the indium mole fraction in QW was determined by comparing of the experimental dependence $A(y_{In})$ with calculated by using our transport model from [3]. The obtained dependence is shown in Figure 3.

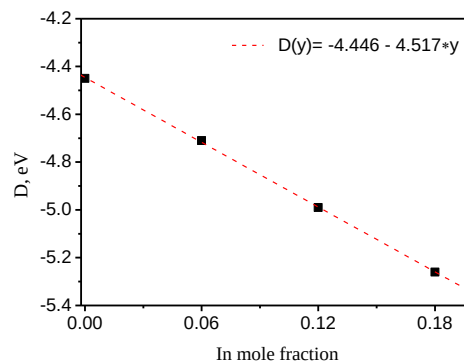


Figure 3. The dependence of deformation potential D on indium mole fraction. Symbols represent the calculated values, dash line shows linear fit.

As one can see, the deformation potential has the linear dependence on y_{In} . But the absolute values of D are less than about twice as widely used values, and grow with increasing y_{In} , whereas they should decrease [4].

Unfortunately, the contribution of the alloy disorder scattering cannot be determined so easy. The mobility limited by alloy disorder scattering μ_{AL} must be reduces with increment of indium mole fraction, because the value of μ_{AL} is inversely proportional to product $y_{In} \times (1 - y_{In})$. But a change in the degree of impurity ionization in the δ -layers closest to the QW, with increment y_{In} , also leads to a change in the ionized impurity scattering. This type of scattering dominates in DA-pHEMT at low temperatures, therefore, it is impossible to determine of parameters of weaker scattering mechanism.

4. Conclusion

The 2DEG density in DA-pHEMT heterostructures with same doping level grows proportionally to the indium mole fraction in QW. The 2DEG mobility decreases at increment of y_{In} at room and liquid nitrogen temperatures. The mobility limited by deformation potential scattering μ_{DP} reduces at increment of y_{In} and lies in range $326\,000 \div 278\,000 \text{ cm}^2\text{V}^{-1}\text{s}^{-1}$ at 77 K for investigated heterostructures. Such a dependence of the μ_{DP} can be explained if it is assumed that the deformation potential varies according to the following law $D(y) = -4.446 - 4.517 \times y$ (eV). Due to change of impurity ionization degree and 2DEG density the change in alloy disorder scattering cannot be determined in the samples under study against the background of variability of stronger scattering by ionized donors.

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