The 2DEG mobility enhancement for low- and high-electric fields in a new type of AlGaAs/InGaAs heterostructures with donor-acceptor doping

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Abstract. The splitting of the delta-layers in the DA-pHEMT heterostructures has resulted in the increase of the spacer’s effective thickness and growth of the low-field 2DEG mobility from 4000÷5000 cm² V⁻¹ s⁻¹ up to 6500 cm² V⁻¹ s⁻¹ at the temperature of 300 K and 2DEG density of 4.0×10¹² cm⁻². The 2DEG mobility in the δ-splitted DA-pHEMT heterostructures almost coincides with the mobility in standard pHEMT heterostructures, but the 2DEG density in the DA-pHEMT heterostructures is approximately twice higher. The additional potential barrier in the DA-pHEMT heterostructures formed by the acceptors causes the reduction of the real-space transfer effect. Therefore, the drift saturation velocity in these heterostructures is higher than the drift saturation velocity in standard pHEMT heterostructures.

1. Introduction

Today the fastest semiconductor transistors are those based on quantum wells (QWs). It has been theoretically predicted that electron and phonon quantization leads to a decrease in the energy relaxation rate of hot electrons and, therefore, allows enhancing ultimate parameters of high-electron mobility transistors (HEMT) [1]. In rather shallow QWs these effects are masked by the real space transfer effect (RST) [2] i.e. the hot electrons escape from a QW into the barriers when the mean electron energy accelerated by a high electric field becomes comparable with the band-gap discontinuity.

Recently we have proposed to increase the effective depth of a QW by modulation doping of QW barriers by donors and acceptors. In this case the height of the barriers is approximately comparable with the band-gap value in the AlGaAs of about 1.5 eV, whereas the height of the barriers without such a doping is limited by the band-gap off-set at the AlGaAs/InGaAs heterointerface of 0.3 eV. A new type of AlGaAs/InGaAs heterostructures with donor-acceptor doped barriers (DA-pHEMT) allows us to suppress the parasitic parallel conductivity via the δ-n-layers placed in the barriers and enhance the output power density of the DA-pHEMT transistor [3]. However, the electron mobility in
DA-pHEMT heterostructures is lowered by scattering on ionized donors from the broadened δ-sublayers located in the barriers [4].

In the present paper we have investigated the influence of the δ-layers splitting on the mobility of two-dimensional electron gas (2DEG) in a low-electric field. The enhancement of the 2DEG mobility in a high electric field due to the suppression of the RST effect by additional potential barriers in DA-pHEMTs has been also studied.

2. Details of the experiments and low-field mobility calculations

The DA-pHEMT heterostructures under study were grown on the (001) GaAs substrate by the molecular-beam epitaxy using the Compact 21T machine. The heterostructure buffer consists of a 0.4 micrometer-thick GaAs layer and twelve-period GaAs/AlAs superlattice. The growth rates were equal to 0.28 nm s⁻¹ at the temperature of 620 °C and 0.24 nm s⁻¹ at the temperature of 500–520 °C for the (Al)GaAs layers and InGaAs layers, respectively. The growth of the δ-layers was carried out at 530 °C. The layer consequence for a DA-pHEMT heterostructure is shown in Figure 1 (without a top n⁺-GaAs contact layer).

The values of the 2DEG density and mobility were determined from the variable-field Hall effect measurement by the Van der Pauw method at 77 K and 300 K temperatures in the magnetic field range of 0–2 T by using the mobility spectrum analysis with multi-carrier fitting [4]. Ohmic contacts to the samples were fabricated by the high-voltage discharge through the indium foil imposed on the sample.

The rectangular mesa-samples were made by photolithography and wet etching to measure drift velocity and electroluminescence (EL). The Ge/Au/Ni/Au ohmic contacts were formed by the electron-beam evaporation and 5-min annealing in a hydrogen atmosphere at 420 °C. The distance between the contacts ranged from 6 to 500 nm for different samples. The velocity-field characteristics were determined from the pulsed current-voltage measurements with a pulse duration of 800 ns. We assume that the 2DEG density does not have any dependence upon an electric field intensity. The EL radiation emitted from the samples under the voltage pulse was measured by the spectrometer on the basis of the single diffraction monochromator equipped with a Si CCD matrix at 300 K.

| Layer                  | Thickness (nm) | Impurity (cm⁻³) |
|------------------------|----------------|-----------------|
| AlGaAs                 | 6              |                 |
| AlGaAs:Be              | 8, 5×10¹⁷      |                 |
| AlGaAs                 | 7              |                 |
| 2ML GaAs               |                |                 |
| δ₅₁                    | 6×10¹⁴          |                 |
| 2ML GaAs               |                |                 |
| AlGaAs spacer          | 3              |                 |
| GaAs spacer            | 1.5            |                 |
| InGaAs                 | 14, x=0.165    |                 |
| GaAs spacer            | 3              |                 |
| AlGaAs spacer          | 3              |                 |
| 2ML GaAs               |                |                 |
| δ₅₁                    | 6.5×10¹³        |                 |
| 2ML GaAs               |                |                 |
| AlGaAs                 | 5              |                 |
| AlGaAs:Be              | 11, 4×10¹⁵     |                 |
| Buffer layers/GaAs substrate |          |                 |

Fig. 1. The layer sequence and doping levels for the DA-pHEMT heterostructure.

Fig. 2. The dependence of the low-temperature 2DEG mobility limited by ionized-donors scattering upon the broadening of δ-layers splitting: dash-dot red line – unsplitted δ-layers, solid green line – 1 nm, dash blue line – 2 nm distance between the δ-sublayers.
The calculations of the 2DEG mobility limited by ionized-donors scattering were made at low temperature (77 K) according to the theoretical model described in our previous paper [4]. The broadening of the δ-layers was taken into account. We assume that the Gaussian distribution with a standard deviation (σ) describes the δ-layer profile. The heterostructure band diagrams and subband wave functions ϕ(δ) required for 2DEG mobility calculations were determined using the self-consistent Schrodinger-Poisson solver NextNano [5].

3. Results and discussion
Splitting of the δ-layers has been proposed to reduce the Coulomb scattering on the ionized donors that dominates at low temperatures in DA-pHEMT heterostructures [4]. So far such splitting has been applied only for suppression of parasitic parallel conductivity [6, 7]. The δ-layers from each side of a QW (see Fig. 1) can be split into two δ-sublayers with the total donor density in the nearest to the QW δ-sublayers equal to the 2DEG density. The donor concentration in the δ-sublayers remote from the QW should be close to the net acceptor concentration for the best compensation. The calculations have shown that δ-layer splitting does not result in a noticeable change in the potential diagram or subband wave functions in the QW region. Nevertheless, the 2DEG mobility limited by scattering on the ionized donors has improved significantly due to the increase in the effective thickness of the spacer. The calculated 2DEG mobility at 77 K for different δ-layers splitting is presented in Fig. 2. As one can see from Fig. 2, the mobility improves from 11230 cm² V⁻¹ s⁻¹ for the zero splitting to 16600 cm² V⁻¹ s⁻¹ for the 2-nm-splitting at the 3.4-nm standard deviation of the δ-layers.

The obtained values of the 2DEG density and mobility are listed in Table 1 for standard pHEMT heterostructures, DA-pHEMT heterostructures with unsplit δ-layers and DA-pHEMT heterostructures with split δ-layers. The parasitic parallel conductivity has been observed for standard pHEMT heterostructures with the density of slightly less than 2×10¹² cm⁻² and mobility of about 1700 cm² V⁻¹ s⁻¹ at the room temperature. As one can see from Table 1, the 2DEG mobility for the DA-pHEMT heterostructures approximately is halved in comparison with the standard pHEMT heterostructures.

This results from a higher density of the ionized donors in both δ-layers which leads to an increase in scattering on the ionized donors [4]. But the 2DEG mobility in DA-pHEMT heterostructures after splitting of the δ-layers becomes comparable with mobility in standard pHEMT heterostructures. Such a mobility enhancement testifies the theoretical calculations shown in Fig. 2.

**Table 1.** The 2DEG density and mobility for the heterostructures under study at 300 K and 77 K.

|          | n₁, ×10¹² cm⁻² | μ₁, cm² V⁻¹ s⁻¹ | n₂, ×10¹² cm⁻² | μ₂, cm² V⁻¹ s⁻¹ |
|----------|----------------|-----------------|----------------|-----------------|
| pHEMT    | 2.5            | 7070            | 2.7            | 19500           |
| pHEMT    | 2.6            | 6900            | -              | -               |
| DA-pHEMT | 3.7            | 4150            | -              | -               |
| DA-pHEMT | 3.4            | 4770            | 3.7            | 11000           |
| splitted DA-pHEMT | 4.0 | 6600             | 4.0            | 21200           |
| splitted DA-pHEMT | 3.9 | 6590             | 4.0            | 19600           |

The electric field dependencies of drift velocity are shown in Fig. 3 for the standard pHEMT heterostructures, DA-pHEMT heterostructures with unsplit δ-layers and DA-pHEMT heterostructures with split δ-layers. As one can see from this figure, the area of negative differential resistance is observed for the standard pHEMT heterostructure, whereas this feature is absent for both DA-pHEMT heterostructures. Moreover, the drift velocity in the DA-pHEMT heterostructures is higher than the drift velocity in the standard pHEMT heterostructure. The splitting of the δ-layers in the DA-pHEMT heterostructure leads to the increase in drift saturation velocity. These peculiarities can be explained by the suppression of the RST effect in DA-pHEMT heterostructures with an additional potential barrier formed by acceptors. Therefore, hot carriers don’t escape from a QW into wide gap barrier layers and possesses a higher drift velocity.
The suppression of the RST effect is also confirmed by the EL measurements. The EL spectrum of a standard pHEMT heterostructure consists of many bands due to the optical transition in various heterostructure layers. The bands related to the optical transitions between the subbands in the InGaAs QW dominate in the spectrum of the DA-pHEMT heterostructures. Therefore, the electrons do not escape from the QW in a high electric field (up to few kV/cm) in the DA-pHEMT heterostructures. The EL intensity becomes saturated at the current of 0.3 A in standard pHEMT heterostructures (see Fig. 4). In case of a DA-pHEMT heterostructure the EL intensity grows up to the maximum applied current of 1.2 A. Such a difference confirms that the high potential barriers in the DA-pHEMT heterostructures suppress the RST effect and the electrons remain confined in high electric fields.

4. Conclusions

It has been shown both theoretically and experimentally that the splitting of the δ-layers leads to a significant increase in a low-field 2DEG mobility in DA-pHEMT heterostructures due to an effective spacer thickness growth and, consequently, reduction of the ionized donor scattering. There is no negative resistance area on field dependencies of drift velocity in DA-pHEMT heterostructures. Besides, the drift saturation velocity in DA-pHEMT heterostructures is higher than the drift saturation velocity in standard pHEMT heterostructures. The bands related to the optical transitions between the subbands in an InGaAs QW dominate in the EL spectra of DA-pHEMT heterostructures. Moreover, the EL intensity doesn’t saturate at an electric field intensity growth in DA-pHEMT heterostructures. These features testify that the RST effect is suppressed in DA-pHEMT heterostructures by an additional potential barrier formed by acceptors.

References

[1] B.K. Ridley, Rep. Prog. Phys., 54, (1991) 169
[2] Z.S. Gribnikov et al, Appl. Phys. Rev., 77(4), (1995) 1337
[3] V. M. Lukashin et al, Semiconductors, 48(5), (2014) 666
[4] D. V. Gulyaev et al, J. Phys. D: Appl. Phys., 49, (2016) 095108
[5] www.nextnano.de
[6] K. Kalna and A. Asenov, Solid-State Electron. 48, (2004) 1223
[7] R. Gupta et al, Microelectronics J., 37 (2006) 919