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Decrease of MODFET channel conductivity with increasing sheet electron concentration

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In modulation-doped field-effect transistor (MODFET) structures, spatial separation of carriers from their parent donors increases electron mobility and enables a modulation doping level with donors, and, consequently, electron concentration in a MODFET channel to be enhanced. Both these factors enhance transconductance and operation speed of MODFET's. There are a lot of attempts to improve MODFET parameters by increasing the modulation doping level with donors.

As is known, AlGaAs/GaAs/AlGaAs and AlGaAs/InGaAs/GaAs MODFET's with the cutoff frequency as high as 400 GHz are created. But the further improvement of high-speed MODFET parameters is restricted because of a decrease of electron mobility with increasing a doping level of the structure.

In the paper, the factors responsible for limitation of MODFET channel conductivity enhancement with increasing sheet electron concentration are considered.

Using the dielectric continuum approximation [1] the calculations of scattering rates of confined electrons by confined polar optical (PO) phonons depending on sheet electron concentration are performed.

A strange effect is observed: the heterolayer conductivity decreases with increasing the electron concentration in the layer. The decrease of mobility exceeds the increase of sheet electron concentration n_s when $n_s > 5 \times 10^{15}\,\mathrm{m}^{-2}$.

Taking into account the electron degeneration, the scattering rate of an electron from the initial state in subband i with the energy E to final states in subband f with the energy $E \pm \hbar\omega_v$ is written as

$$W_{if}(E) = \sum_v W^e_{ifv} \frac{1 - f(E - \hbar\omega_v)}{1 - f(E)} + W^a_{ifv} \frac{1 - f(E + \hbar\omega_v)}{1 - f(E)} \tag{1}$$

where $f(E)$ is the Fermi–Dirac distribution function, the superscripts e and a correspond to the phonon emission and absorption, respectively. The inverse electron life time τ_i in the state E of subband i limited by optical phonon scattering can be determined as

$$\frac{1}{\tau_i(E)} = \sum_f W_{if}(E). \tag{2}$$

For estimation of the electron mobility limited by PO phonon scattering we involve the life time $\tau_i(E)$ as momentum relaxation time. Then the mobility in subband i is determined as

$$\mu_i = \frac{2}{m} \left\langle \frac{1}{\tau_i(E)} \right\rangle^{-1} \tag{3}$$

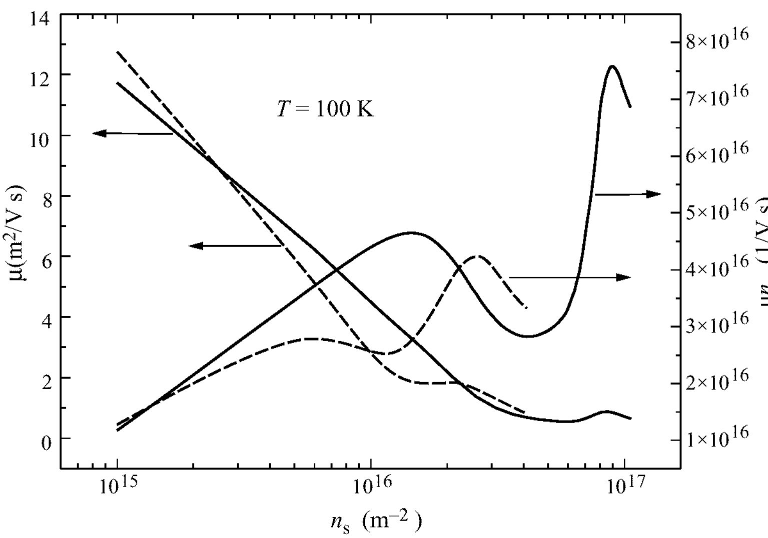

Fig. 1. Mobility μ and conductivity μn_s in $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW with an inserted thin barrier (solid lines) and without it (dashed lines) at 100 K as functions of sheet electron concentration n_s.

where the brackets $\langle\rangle$ mean the average value:

$$\langle A\rangle = \frac{\int Af(E)\mathrm{d}E}{\int f(E)\mathrm{d}E}.$$

The average electron mobility in the QW is

$$\mu = \sum_i \mu_i \frac{n_{si}}{n_s} \tag{4}$$

where

$$n_{si} = D\int_{E_{si}}^{\infty} f(E)\mathrm{d}E \tag{5}$$

is the concentration of electrons in subband with the bottom energy E_{si}, $D = m/\pi\hbar^2$ and $n_s = \sum_i n_{si}$.

In Fig. 1 the calculated electron mobility as a function of sheet electron concentration n_s in the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW is presented.

One can see that, taking into account only electron-PO phonon scattering, calculated mobility decrease at 100 K exceeds the sheet electron concentration increase in the range of $n_s = (6-10) \times 10^{15}\ \mathrm{m}^{-2}$. As a result, the negative change of the channel conductivity (represented in Fig. 1 as the mobility multiplied by the electron concentration: μn_s) takes place.

It allows us to expect that the great electron-PO phonon scattering increase is the main factor responsible for the great decrease of the mobility and conductivity observed experimentally at high sheet electron concentrations in AlGaAs/GaAs/AlGaAs QW's.

In the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW the alternate increase and decrease of the calculated channel conductivity μn_s with increasing n_s are observed. The channel QW conductivity of MODFET can be increased by increasing the doping level. The conductivity when $n_s = 2.5 \times 10^{16}\,\mathrm{m}^{-2}$ exceeds the conductivity at $n_s = 6 \times 10^{15}\,\mathrm{m}^{-2}$ (see Fig. 1).

Each cycle of the alternate decrease-increase conductivity change with increasing n_s corresponds to the change of the Fermi level position E_F with respect to the QW subband energy level E_s . In the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW at 100 K, the Fermi level crosses two subband energy levels when the sheet electron concentration changes from $n_s = 10^{15}\,\mathrm{m}^{-2}$ to $n_s = 10^{17}\,\mathrm{m}^{-2}$. Correspondingly, two conductivity increase-decrease cycles are observed (see Fig. 1).

The insertion of a thin AlAs barrier into the GaAs QW center changes the electron subband energies. This admits a possibility for increasing the doping level and the maximal channel conductivity. This is shown in Fig. 1 where the calculated mobility μ and channel conductivity μn_s for $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW with an inserted thin AlAs barrier as functions of doping level are represented.

The increase of maximal doping limits determinates the possibilities of enhancement of high-speed parameters for $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ MODFET's.

References

[1] J. Požela, A. Namajënas, K. Požela and V. Jucienè, *Physica E* **5**, 108 (1999).