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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 $n_s > 5 \times 10^{15}$ 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

$$W_{if}(E) = \sum_v W_{ifv}^e \frac{1 - f(E - \hbar \omega_v)}{1 - f(E)} + W_{ifv}^a \frac{1 - f(E + \hbar \omega_v)}{1 - f(E)}$$

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 $\tau_i$ in the state $E$ of subband $i$ limited by optical phonon scattering can be determined as

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

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

$$\mu_i = \frac{2}{m} \left( \frac{1}{\tau_i(E)} \right)^{-1}$$
Fig. 1. Mobility $\mu$ and conductivity $\mu n_s$ 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:

$$\langle A \rangle = \frac{\int A f(E) dE}{\int f(E) dE}.$$  

The average electron mobility in the QW is

$$\mu = \sum_i \mu_i \frac{n_{si}}{n_s}$$  \hspace{1cm} (4)

where

$$n_{si} = D \int_{E_{si}}^\infty f(E) dE$$  \hspace{1cm} (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 $n_s = (6-10) \times 10^{15}$ m$^{-2}$. As a result, the negative change of the channel conductivity (represented in Fig. 1 as the mobility multiplied by the electron concentration: $\mu n_s$) 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 $\mu n_s$ with increasing $n_s$ are observed. The channel QW
conductivity of MODFET can be increased by increasing the doping level. The conductivity when \( n_s = 2.5 \times 10^{16} \, \text{m}^{-2} \) exceeds the conductivity at \( n_s = 6 \times 10^{15} \, \text{m}^{-2} \) (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 \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{As/GaAs/Al}_{0.25}\text{Ga}_{0.75}\text{As} \) QW at 100 K, the Fermi level crosses two subband energy levels when the sheet electron concentration changes from \( n_s = 10^{15} \, \text{m}^{-2} \) to \( n_s = 10^{17} \, \text{m}^{-2} \). 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 \( \mu \) and channel conductivity \( \mu n_s \) for \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{As/GaAs/Al}_{0.25}\text{Ga}_{0.75}\text{As} \) 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 \( \text{Al}_{0.25}\text{Ga}_{0.75}\text{As/GaAs/Al}_{0.25}\text{Ga}_{0.75}\text{As} \) MODFET's.

References