DECREASE OF MODFET CHANNEL CONDUCTIVITY WITH INCREASING SHEET ELECTRON CONCENTRATION

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ABSTRACT

The great decrease of electron mobility with increasing sheet electron concentration n_s *in modulation-doped AlGaAs/GaAs/AlGaAs quantum wells is observed. This effect is explained by increasing scattering of degenerated electrons by polar optical phonons. At* $n_s > 10^{15}$ m^{-2}*, the mobility decrease exceeds the increase of* n_s*, and the channel conductivity decreases with increasing* n_s*.*

INTRODUCTION

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 a transconductance and operation speed of MODFETs. There are a lot of attempts to improve MODFET parameters by increasing the modulation doping level with donors.

As is known, AlGaAs/GaAs/AlGaAs MODFETs with the cutoff frequency as high as a few hundred GHz are created. But the further improvement of high-speed MODFET parameters is restricted because of experimentally observed decrease of electron mobility with increasing doping level of the structure.

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

ELECTRON MOBILITY LIMITED BY POLAR OPTICAL PHONON SCATTERING

The calculations of scattering rates for electrons confined in a quantum well (QW) by confined polar optical (PO) phonons depending on sheet electron concentration are performed using the dielectric continuum approximation [1].

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

$$W_{if}(E) = \sum_\nu W_{if\nu}^e \frac{1 - f(E - \hbar\omega_\nu)}{1 - f(E)} + W_{if\nu}^a \frac{1 - f(E + \hbar\omega_\nu)}{1 - f(E)}\ , \qquad (1)$$

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

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

For estimation of 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

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

where the brackets $\langle \; \rangle$ mean the average value : $\langle A \rangle = \int A\, f(E)\, dE \Big/ \int f(E)\, dE$.

The average electron mobility in the QW is

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

where

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

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

A main peculiarity of nonelastic electron–PO phonon scattering is the increase, by more than two orders of magnitude, of the scattering intensity by PO phonon emission when the electron kinetic energy becomes larger than the phonon energy. A part of the subband electron concentration with the energy *E* larger than $\hbar\omega_V$, $n_S(E > \hbar\omega_V)$, increases with increasing the total subband electron concentration n_S (see Fig. 1). This allows us to expect the great decrease of subband electron mobility when the subband electron gas degenerates.

The calculations of electron mobility taking into account only intrasubband electron–PO phonon scattering show the great decrease of the mobility with increasing the sheet electron concentration in MODFET QW. Figure 1 shows that the change of the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW conductivity (represented as the mobility multiplied by electron concentration: μn_S) is negative at E_F >0.026 eV. This means that the mobility decrease with increasing the ratio $n_S(E > \hbar\omega_V)/n_S > 8 \cdot 10^{-2}$ exceeds the increase of the sheet electron concentration n_S.

DECREASE OF ELECTRON MOBILITY AND CONDUCTIVITY WITH INCREASING SHEET ELECTRON CONCENTRATION

In Fig. 2 the calculated electron mobility, taking into account the inter- and intrasubband electron scattering by confined and interface PO phonons, as a function of sheet electron concentration n_s is presented for the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW.

One can see that, taking into account only electron–PO phonon scattering, the calculated mobility decrease at 100 K exceeds the sheet electron concentration increase in the range of n_s = (6–10)$\times10^{15}$m^{-2}. As a result, the negative change of the channel conductivity (in Fig. 2 represented as μn_S) takes place. Similar results are obtained for the $Al_{0.25}Ga_{0.75}As/In_{0.2}Ga_{0.8}As/GaAs$ QW.

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 MODFET channels.

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. In the $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ case the conductivity maximum when $n_S = 2.5\times10^{16}$ m^{-2} exceeds the conductivity maximum at $n_S = 6\times10^{15}$ m^{-2} (see Fig. 2).

Each cycle of the alternate increase-decrease 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 three subband energy levels when the sheet electron concentration changes from $n_S = 10^{15}$ to 10^{17} m^{-2} . Correspondingly, three conductivity increase-decrease cycles are observed (see Fig. 2).

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. 2 where the calculated channel conductivity $\mu\ n_s$ for $Al_{0,25}Ga_{0,75}As/GaAs/Al_{0,25}Ga_{0,75}As$ QW with an inserted thin AlAs barrier as a function of doping level is represented.

The increase of maximal doping limits determines the possibilities of high-speed parameter enhancement for $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ MODFETs.

The negative channel conductivity dependence on the carrier concentration can be used for designing new type FETs and logic IC elements.

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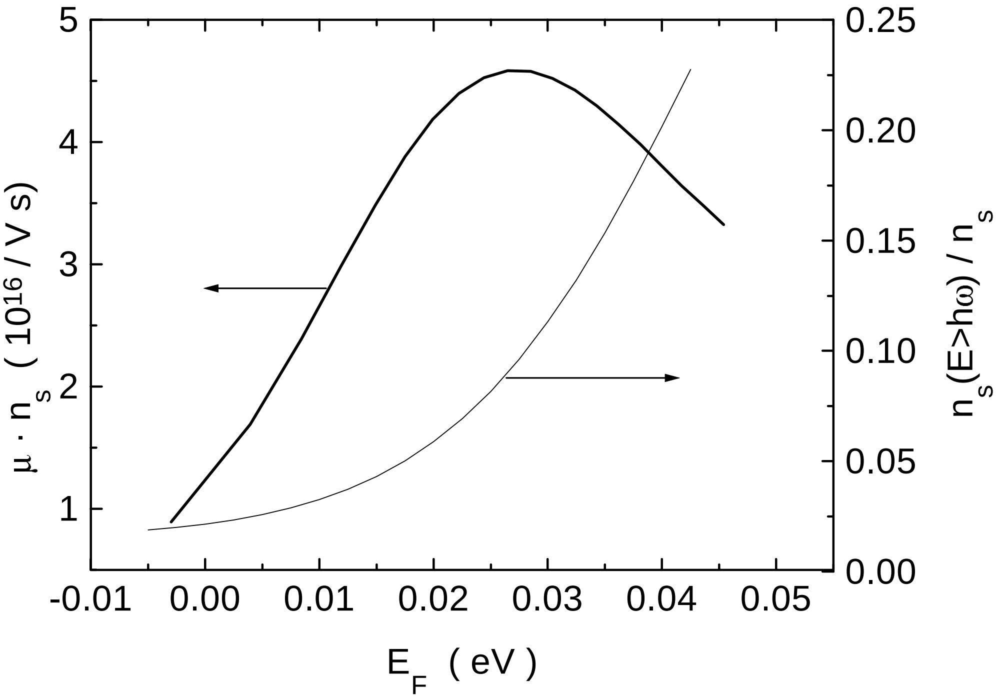

Fig. 1. The ratio $n_s(E>\hbar\omega_V)/n_s$ and the lower subband conductivity (μn_s) of $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW calculated taking into account only intrasubband electron-PO phonon scattering as functions of Fermi level position with respect to the subband bottom energy.

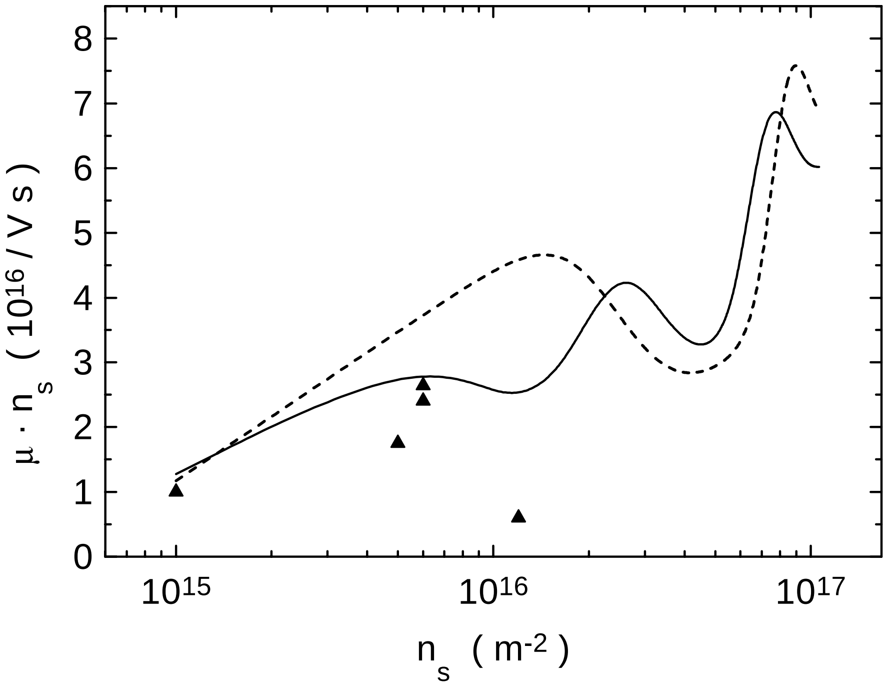

Fig. 2. The conductivity (μn_s) of $Al_{0.25}Ga_{0.75}As/GaAs/Al_{0.25}Ga_{0.75}As$ QW (of width L=20 nm) with an inserted barrier (dashed line) and without it (solid line) at 100 K as a function of sheet electron concentration n_s. The experimental data (triangles) measured at 77 K are from Ref.[2].