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Transport Phenomena in Two-Dimensional Structures with Quantum Dots

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A model that explains the unusual characteristics of the AlGaAs/GaAs modulation-doped field-effect transistor (MODFET) with InAs quantum dots incorporated in the GaAs channel is presented. It is shown that the negative charge of electrons confined in quantum dots decreases the threshold gate-drain voltage at which the channel is fully depleted. This provides an impact ionization of quantum dots at a low drain voltage. Because of the quantum dot ionization, the quantum dot MODFET transconductance becomes large and negative. The increased transconductance, due to the additional doping of the GaAs and InAs channels by impurities, exceeds 10^3 mS/mm. It is shown that the insertion of InAs quantum well with quantum dots into the GaAs quantum well increases the electron maximum drift velocity up to 10^8 cm/s, and consequently, quantum dot MODFET current gain cut-off frequency up to few hundred gigahertz.

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1. Introduction

A thin pseudomorphic InAs layer (wetting layer) incorporated in the GaAs matrices leads to the formation of a deep narrow quantum well (QW). Above a critical wetting layer thickness, self-assembled InAs quantum dots (QDs) are formed. The QDs give rise to discrete, zero-dimensional bound states. A band diagram of the structure is shown in Fig. 1.

These structures were used for creation of new type of AlGaAs/GaAs modulation-doped field-effect transistor, with InAs quantum dots in a channel (QD-MODFET) [1]. The $I-V$ characteristics of QD-MODFET are principally different from those of a conventional MODFET [2, 3]. The transconductance of QD-MODFET changes its sign depending on the drain voltage. A negative transconductance means that, in contrast to a conventional MODFET, the negative gate bias enhances the electron concentration in a QD-channel.

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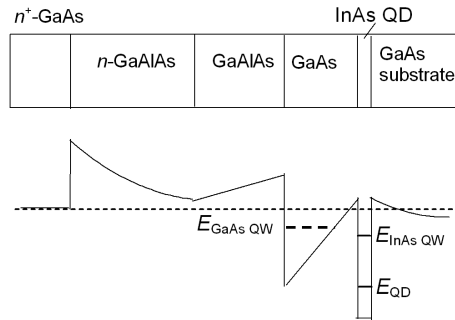


Fig. 1. A conduction band-edge schematic diagram of modulation-doped AlGaAs/GaAs heterostructure with incorporated InAs QW that contains QDs. $E_{\text{GaAs QW}}$, $E_{\text{InAs QW}}$ are the energy levels of the ground subband in GaAs and InAs QWs, E_{QD} is the energy level of confined states in QDs.

In this paper, a model that explains unusual characteristics of such QD-MODFET is developed. The methods that allow to increase the transistor cut-off frequency upwards to hundred gigahertz are proposed.

2. Drain current of QD-MODFET structure

A schematic view of QD-MODFET structure is shown in Fig. 2. Figure 3 shows the measured characteristics of the QD-MODFET with a high concentration of QDs in the channel ($n_d > 10^{11} \text{ cm}^{-2}$). The dependences of the QD-MODFET

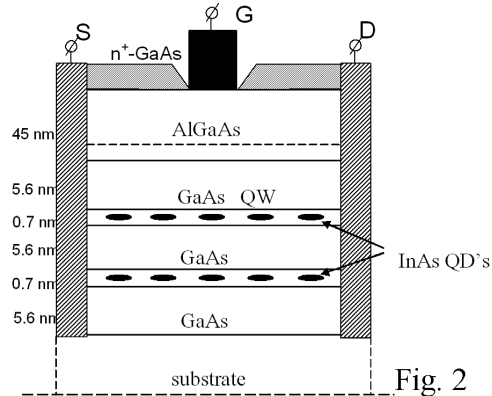


Fig. 2

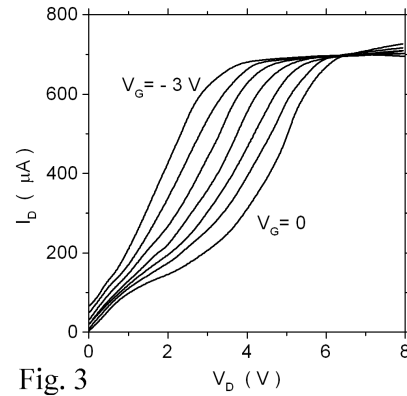


Fig. 3

Fig. 2. A sequence of layers for modulation-doped AlGaAs/GaAs heterostructures with incorporated InAs QW with QDs. The dotted line shows a Si δ -doped layer. The source, gate, and drain contacts are labeled by S, G, and D.

Fig. 3. The dependences of the experimentally measured drain current I_D on the drain voltage V_D for the QD-MODFET with a submicron gate ($W_g = L_g = 0.4 \mu\text{m}$). The step of V_G variation equals 0.5 V.

channel current on the drain and gate voltages have specific peculiarities that are essentially different from those of the conventional MODFET. One of these peculiarities is the change of transconductance sign with the drain voltage, and the second one is the independence of the saturated drain current on the gate voltage.

The drain current through the MODFET channel with InAs QDs can be written as

$$I_D = \frac{e\mu W_g C}{L_g e} \int_0^{V_D} \left[(V_G + V_T - \varphi) - \frac{e}{C} n_d \right] d\varphi. \quad (1)$$

Here W_g and L_g are the width and length of the QW channel, e and μ are the electron charge and electron mobility, respectively, C is the effective gate-channel capacity, n_d is the number of electrons confined in the QDs. The electrons localized at QDs do not participate in the drain current. V_D and V_G are the drain and gate voltages, respectively, φ is the electric potential along the MODFET channel. The threshold voltage V_T is determined as $V_T = \frac{e}{C} n_{S0}$, where n_{S0} is the equilibrium concentration of carriers in the channel. The effective gate capacity C is reduced due to the gate-channel leakage current through the AlGaAs and n^+ -GaAs surface layers (Fig. 2).

After the integration of Eq. (1) over φ we obtain

$$I_D = \frac{e\mu W_g C}{L_g e} \left[(V_G + V_T) V_D - \frac{V_D^2}{2} - \frac{e}{C} n_d V_D \right], \quad \text{at} \quad V_D < V_{D1}, \quad (2)$$

where

$$V_{D1} = V_G + V_T - \frac{e}{C} n_d \quad (3)$$

is the threshold drain voltage at which the current I_D is saturated ($dI_D/dV_D = 0$). A negative charge of n_d electrons localized in QDs leads to a strong decrease in threshold voltage V_{D1} .

The highest electric field is created at the gate edge on the drain side when the drain current is saturated, and the impact ionization of QDs will take place in this high-field channel region. As a result of QD ionization, electrons escape out of QDs and contribute to the drain current: $\frac{e\mu W_g}{L_g} n_d (V_D - V_{D1})$. Their contribution increases with increase in drain bias, due to the expansion of the high-field region in the channel.

Thermal ionization of impurities located in the channel additionally fills the QDs by n_{d0} electrons. A negative charge of these additional n_{d0} electrons trapped at the QDs is compensated by their impurity charge, and therefore, the neutral QDs do not change the potentials in the channel. However, the ionization of the neutral QDs in a high electric field gives an additional contribution to the drain current. The total contribution of electrons ionized from the QDs to the drain

current is

$$\Delta I_D = \frac{e\mu W_g}{L_g} (n_d + n_{d0})(V_D - V_{D1}). \quad (4)$$

Therefore, at $V_D > V_{D1}$, the drain current becomes

$$I_D = \frac{e\mu W_g C}{L_g e} \left[(V_G + V_T)V_D - \frac{V_D^2}{2} - \frac{e}{C} n_d V_{D1} + \frac{e}{C} n_{d0}(V_D - V_{D1}) \right], \quad (5)$$

at $V_D > V_{D1}$.

In Eq. (5) it is assumed that the term $(V_G + V_T)V_D - V_D^2/2$ is saturated at $V_D \geq V_G + V_T$ and reduces to $(V_G + V_T)^2/2$. The other two terms in Eq. (5) characterize an increase in I_D in the saturation area due to ionization of QDs by a high electric field.

Figure 4a demonstrates $I_D(V_D)$ curves at different V_G magnitudes calculated with Eqs. (2) and (5), using the following channel parameters: $\frac{C}{e} = 4 \times 10^{10} \text{ V}^{-1} \text{ cm}^{-2}$; $n_{d0} = 4 \times 10^{10} \text{ cm}^{-2}$; $n_d = 2.8 \times 10^{11} \text{ cm}^{-2}$; $V_T = 10 \text{ V}$; $\mu = 3 \times 10^3 \text{ cm}^{-2} \text{ V}^{-1} \text{ s}^{-1}$; $W_g = L_g = 0.4 \text{ }\mu\text{m}$. The gate leakage current $I_g = 20(V_D - V_G) \text{ }\mu\text{A}$ is taken into account. One can see the change of the transconductance sign when V_D becomes larger than V_{D1} .

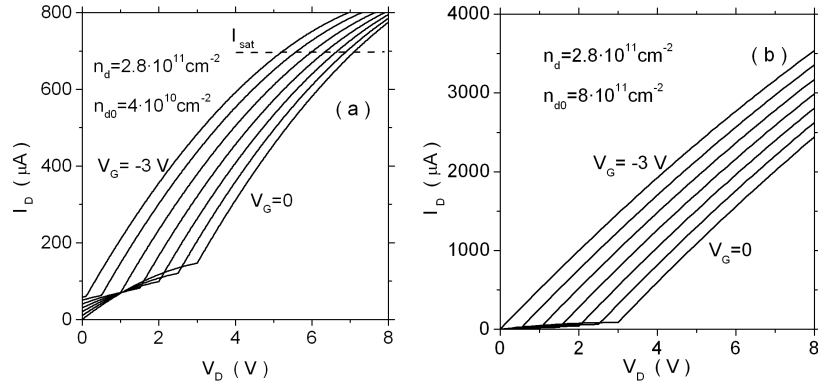


Fig. 4. Calculated $I_D(V_D)$ dependences for the QD-MODFET with (a) low ($n_{d0} = 4 \times 10^{10} \text{ cm}^{-2}$) and (b) high ($n_{d0} = 8 \times 10^{11} \text{ cm}^{-2}$) number of electrons localized at QDs. The step of V_G variation equals 0.5 V . I_{sat} is the saturated drain current.

Figure 4b demonstrates the strong increase in the drain current in a case when $n_{d0} = 8 \times 10^{11} \text{ cm}^{-2}$.

The calculated $I_D(V_D)$ curves (Fig. 4a) are in good agreement with the experimental ones (Fig. 3) except when the calculated drain current exceeds $700 \text{ }\mu\text{A}$. The experimentally measured I_D shows the saturation at this level of the current.

3. Negative transconductance of QD-MODFET and drain current saturation

The transconductance is equal to

$$g_m = \frac{1}{W_g} \frac{\partial I_D}{\partial V_G} = \frac{e\mu}{L_g} \left[\frac{C}{e} V_D - (n_d + n_{d0}) \right], \quad V_D > V_{D1}. \quad (6)$$

Its value is determined by the density of electrons confined in the QDs. One can see that the QD-MODFET transconductance has two contributions: the positive part $\propto \frac{C}{e} V_D$ and the negative one $\propto (n_d + n_{d0})$. At $\frac{C}{e} V_D > n_d + n_{d0}$ (this condition is satisfied in transistors with a low electron density, $n_d + n_{d0}$), the transconductance is positive. At $\frac{C}{e} V_D < n_d + n_{d0}$, the transconductance becomes negative. This takes place in transistors with a high concentration of electrons confined in the QDs. The AlGaAs layer between the gate and channel, and the n^+ -GaAs surface layer are responsible for the essential reduction of the effective gate capacitance C , and therefore, for the decrease in the positive transconductance part ($\propto \frac{C}{e} V_D$).

The absolute value of the experimentally observed negative transconductance at $V_D = 2$ V and $V_G = -2$ V (Fig. 3) is equal to $|g_m| = 400$ mS/mm. The estimation of the negative transconductance made from the calculated I - V characteristics at $V_D = 2$ V and $V_G = -2$ V also gives $|g_m| = 400$ mS/mm (Fig. 4a).

It is worth noting that the increase in the electron concentration n_{d0} in the channel due to additional doping increases the absolute value of the negative transconductance. Figure 5 shows the calculated dependence of g_m on V_D with

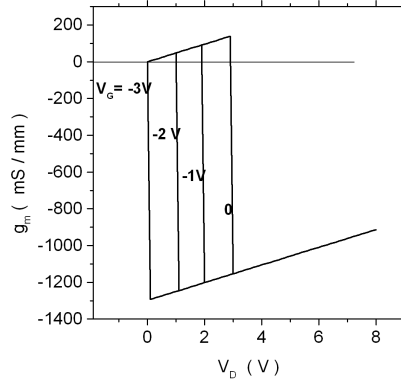


Fig. 5. Calculated dependences of transconductance g_m as a function of drain voltage V_D and gate voltage V_G for the QD-MODFET.

n_{d0} increased up to $8 \times 10^{11} \text{ cm}^{-2}$. One can see that the increase in n_{d0} magnifies g_m up to 1300 mS/mm, which is much larger than the value of g_m in MODFET without QDs.

The negative transconductance of the QD-MODFET decreases when the drain current and voltage increase. At $V_D \approx \frac{e}{C} n_d$, it is close to zero, and at larger

V_D value it changes sign. At the drain current saturation, the transconductance is close to zero because I_D is independent of V_G .

The experimental data (Fig. 3) demonstrate a specific effect: the saturation of QD-MODFET drain current, which appears to be nearly independent of the gate bias. Two factors are responsible for the independence of the saturated drain current on the gate bias. Firstly, at the large drain current, when all QDs are ionized, only small part of full electron concentration can be regulated by the gate bias. Secondly, at the sheet electron concentration larger than $n_s > 5 \times 10^{11} \text{ cm}^{-2}$, the conductivity of the GaAs channel, according to Ref. [4], is nearly independent of the electron sheet concentration.

For the drain current saturation, the electron drift velocity saturation at high electric fields appears to be responsible. The maximum value of the drain current in the QD-MODFET was estimated to be $I_{\text{sat}} \approx 700 \mu\text{A}$, as shown in Fig. 4a.

4. Increase in electron drift velocity and cut-off frequency of current gain

High-speed parameters of the field-effect transistors are determined by a maximal electron drift velocity value, $v_{d \text{ max}}$, at high electric fields. The current gain cut-off frequency of a FET can be estimated from

$$f_T = v_{d \text{ max}}/2\pi L_g, \quad (7)$$

where L_g is the gate length.

The increase in f_T is usually obtained by decreasing the gate length L_g up to submicrometer lengths. However, let us consider the possibilities to increase f_T by increasing the maximal electron drift velocity in a GaAs channel of the QD-MODFET.

The electron scattering with emission of polar optical (PO) phonons is the main limiting mechanism responsible for maximal drift velocity. An electron accelerated in an electric field up to PO phonon energy, $\hbar\omega_0$, after inelastic scattering with the emission of the optical phonons is stopped [5]. Consequently, in a bulk semiconductor, the maximal drift velocity v_{m0} achieved in the electric field, and the maximal value of the electron momentum are equal to

$$v_{m0} = \sqrt{\frac{2\hbar\omega_0}{m}}, \quad k_{\text{opt}} = \sqrt{\frac{2m\hbar\omega_0}{\hbar^2}}. \quad (8)$$

The emitted optical phonon momentum is

$$q_{\text{opt}} = k_{\text{opt}} = \pi/L_{\text{opt}}. \quad (9)$$

The mean drift velocity can be estimated as

$$v_{\text{dm}} = v_{m0}/2. \quad (10)$$

For GaAs $v_{m0} = 4.4 \times 10^7 \text{ cm/s}$ and $L_{\text{opt}} = 12.8 \text{ nm}$. The cut-off frequency of a GaAs FET with $L_g = 10^{-4} \text{ cm}$ is $f_T = 35 \text{ GHz}$.

The QD-MODFET channel is a layered structure, where InAs thin layers are inserted into the GaAs matrix QW (Fig. 2). The PO phonon momentum in GaAs layer with a thin InAs monolayer inside is quantized, because of different PO phonon energies in these materials (36 meV and 29 meV, respectively). The phonon momentum in z -direction of structure growth is equal to

$$q_z = n \frac{\pi}{L_z}, \quad (11)$$

where n is the integer, and L_z is the length of the GaAs layer between the AlGaAs and InAs phonon barriers.

The phonon quantization essentially changes the electron–PO phonon interaction. Figure 6 illustrates that there are only four possible phonon momentum values that can be emitted (absorbed) by an electron with the energy E_i .

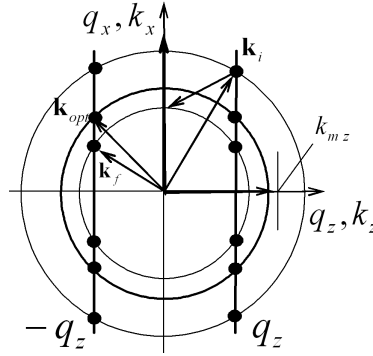


Fig. 6. x, y plane of electron (\mathbf{k}) and phonon (\mathbf{q}) wave vectors. $q_z = n\pi/L_z$ is the discrete value of z -component of confined phonon wave vector. The black points show the values of phonon wave vectors that can be emitted (absorbed) by electrons with moments $\mathbf{k}_i, \mathbf{k}_{\text{opt}}, \mathbf{k}_f$. The transfer of an electron from the state \mathbf{k}_i to the state \mathbf{k}_f after a phonon emission is shown.

In the case of the optical phonon confinement in the GaAs layer, the momentum and energy conservation laws for electron–phonon interaction are

$$k_i^2 = k_f^2 \pm k_{\text{opt}}^2, \quad k_z = k_{fz} \pm q_z, \quad (12)$$

where k_i and k_f are the initial and final (after interaction with the phonon) electron momenta, respectively. The sign “+” corresponds to emission, and “−” to absorption of a confined phonon.

For electron flow in the direction x in the plane of InAs and GaAs layers ($k_{iz} = 0$) the conservation laws (12) give

$$k_{ix}^2 = k_{fx}^2 + q_z^2 \pm k_{\text{opt}}^2. \quad (13)$$

The scattering with phonon emission takes place at $k_{ix} \geq k_{ix}^*$, where

$$k_{ix}^* = \sqrt{q_z^2 + k_{opt}^2}. \quad (14)$$

The mean electron drift velocity in x -direction can be estimated as

$$v_{dx \max} = \frac{\hbar}{2m} (k_{ix}^* + q_z). \quad (15)$$

The enhancement of the electron maximal drift velocity, compared with that without the phonon confinement, Eq. (10), can be characterized by the ratio

$$\eta_x = \frac{v_{dx \max}}{v_{dm}}. \quad (16)$$

In the QD-MODFET structure under study, $L_z = 5.6$ nm, $L_{opt} = 12.8$ nm, and the drift velocity shows a fivefold increase.

However, the presence of InAs layer in GaAs matrix will give rise to interface PO phonons. The electron interaction with interface phonons decreases the electron mobility and drift velocity and, thus, compensates the increase in electron mobility and drift velocity due to confinement of bulk phonons [6–9].

The interface phonon wave vector q_x^{IF} lies in the InAs layer plane. The electron flow in the x -direction with the momentum k_x interacts with the interface phonons.

The electrons with the momentum k_z perpendicular to the InAs layer plane do not interact with the interface phonons since the z -component of the phonon wave vector is absent, $q_z^{IF} = 0$ [9].

Let us consider the electron flow perpendicular to the InAs layer plane. We propose that a thin InAs barrier does not disturb the electron flow in z -direction.

At $k_{ix} = 0$ the conservation laws (12) give the singular value for the k_{iz} component

$$k_{iz}^* = \frac{k_{opt}^2 \pm q^2}{2q_z}, \quad (17)$$

where the sign “+” corresponds to emission, and “–” to absorption of the optical phonon. Therefore, only the electron with the wave vector k_{iz}^* is scattered by a phonon.

The mean electron drift velocity in z -direction, according to Eqs. (10) and (17), can be estimated with

$$v_{d \max z} = \frac{\hbar}{4m} \left(\frac{k_{opt}^2}{q_z} + 3q_z \right). \quad (18)$$

The increase in the drift velocity in z -direction then is

$$\eta_z = \frac{v_{d \max z}}{v_{dm}} = \frac{1}{2} \left(\frac{L_z}{L_{opt}} + 3 \frac{L_{opt}}{L_z} \right). \quad (19)$$

The electron drift velocity in the MODFET GaAs channel, which is divided by a

vertically inserted every 5.6 nm InAs layers, will increase by a factor 3.6. Consequently, the transistor cut-off frequency f_T will reach few hundred gigahertz.

For electron flow in the z -direction the scattering with phonon absorption takes place only at k_{iz}^* (Eq. (17)). Hence, the electron mobility at a low field, when $k_{iz} < k_{iz}^*$, will not be limited by the optical phonon scattering and will be much larger than it is in a bulk material.

Consequently, the electron drift velocity perpendicular to the phonon quantization direction is much larger than that in a bulk semiconductor. It is worth noting that electron–interface phonon scattering does not compensate this increase.

In the QD-MODFET under consideration, the InAs QW contains many QDs, so the interface phonon quantization will take place. This property favours the elimination of the interface phonon influence on the electron drift velocity along the GaAs channel. The maximal drift velocity in the GaAs channel, according to Eq. (16), can increase up to 10^8 cm/s, and consequently, the current gain cut-off frequency of the transistor with $L_g = 0.4$ μm will reach $f_T \approx 400$ GHz.

5. Conclusions

1. The QD-MODFET is a new semiconductor device with specific parameters:
 - (a) The transconductance g_m changes its sign depending on the magnitude of V_D and V_G .
 - (b) The absolute value of g_m can be achieved much larger than in the conventional transistors.
2. The current gain cut-off frequency f_T of GaAs QD-MODFET can be increased up to a few hundred GHz by using the heterostructure with phonon momentum quantization. The layered structure, where InAs barriers with QDs are inserted in GaAs is proposed as a device which favours the increase in the maximal electron drift velocity, and consequently, transistor cut-off frequency f_T .

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