NEW SOLID STATE TRANSISTOR BASED ON THE QUANTUM DOT SYSTEM

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ABSTRACT

Modulation doped N-AlGaAs/GaAs/InAs/GaAs/InAs/GaAs-heterostructures with quantum dots in device channel have been grown and investigated. Their electron transport properties both in low and high electric fields were studied. Using these structures, modulation doped FET's have been fabricated and analyzed. It was demonstrated, that the operation of such a transistor reminds that of vacuum triod, where the gate electrode, similar to the grid electrod in vacuum triod, controls the electron emission out of their source – self organized ensemble of quantum dots.

INTRODUCTION

Recently it has become possible to fabricate laterally defined nanostructures, such as quantum dots (QD's). Properties of zero-dimensional electrons confined in such structures attract a great interest both in physics and device applications. The most promising nanometer (nm)-scale QD-structures are formed by the Stranski – Krastanov mode of the heteroepitaxial growth in which a material is deposited on a lattice mismatched substrate beyond some critical thickness to form very small dot structures (~20nm) [1]. Although much work has been done on the structural and optical properties of QD's, relatively little is known on the influence of the dot-induced potentials on transport of electrons flowing in the neighborhood of dots, particularly, in high electric fields, and on the operation of the real QD-modulation doped field effect transistors (QD-MODFET's). In this work we study the electron transport properties of the modulation doped N-AlGaAs/GaAs/InAs/GaAs/InAs/GaAs-heterostructures with the InAs-dots embedded in the GaAs-channel, and analyze the characteristics of QD-MODFET's fabricated on their basis. It was shown that mobility μ_{2D} and concentration n_{2D} of 2D-electrons are strongly influenced by QD's. The high field current-voltage-characteristics (I-V-C's) of MODFET's exhibit the strong contribution from the electrons confined in QD's. QD-devices demonstrate the new type of the hot electron transistors which can be promising for high speed applications.

MBE GROWTH OF QD MODFET-STRUCTURES

QD-MODFET-structures (samples S1) studied here have been grown by molecular beam epitaxy (MBE) on (100)-semi-insulating GaAs-substrates. Fig.1 shows schematically their cross section. As a reference sample (RS), we also grew the pseudomorphic-MODFET-structure without QD's with the same average $In_{0,17}Ga_{0,83}As$ composition of the 12nm-thick channel layer.
Fig 2 shows AFM-photograph of the sample S1, in a case of which the MBE-growth was completed immediately after growing the second InAs layer. According to this Fig., the average size of QD's and their areal density are 30÷40nm and $3 \cdot 10^{10} cm^{-2}$, respectively.

LOW AND HIGH FIELD ELECTRON TRANSPORT IN QD-SYSTEM

In the results of the Hall effect measurements it was shown that the insertion of QD's into the device channel results in a reduction of μ_e and n_{2D}. The latter was associated with the trap of majority of electrons by QD's. The change (reduction) of electron mobility in sample S1, as compared with sample RS, is the direct indication of the essential Coulomb interaction of the mobile 2D electrons with those confined in QD's.

Because the essential part of electrons in samples S1 is trapped by QD's, they can not participate in the low field electric transport. However, their contribution can be displayed at higher fields. For such experiments, special MODFET's with a the 2μm-drain-to-source spacing, without gate and with different widths of the ohmic contacts have been fabricated. Their I-V-C's are shown in Fig.3. As seen from this Fig, in contrast to "standard" FET's, they display the anomalous "two-step" shape (instead of the conventional curve with "saturation").

The anomalous I-V-dependence in Fig.3 has been associated with the specific behaviour of the electrons confined in QD's, which get out of QD's with increasing an electric field F. We also took into account, that such a steep increase of current (at $F>10^4$V/cm) after the previous saturation is usually associated with effect of impact ionization. Very similar voltage dependence, explained by impact ionization, has been earlier observed for the photo-current – voltage characteristics in MQW-heterostructures (along the growth direction) [3], where the preliminary excitation of electrons inside the QW's was initiated by the infrared radiation. The subband energies in [3] were approximately the same order of magnitude as the energy levels in QD's studied here. However in our case, instead of the photoexcitation, the required population of the excited states in QD's has been made technologically during MBE growth of the modulation doped structure.

The supposed here process of the impact ionization of electrons out of the ground state E_1 of QD is schematically indicated in Fig.4. It can be initiated both by the hot mobile 2D electrons and by the hot electrons getting or tunneling out of the QD-excited states E_n. Both of these electrons are directly responsible for the device current at the low and moderate values of the drain-source voltage, i.e., for the first step of I-V-characteristics. The reduction of the first step current after the surface etching (see Fig.3, curves b and c) is a result of the enhanced surface potential depletion of the channel. After interaction of an incident hot electron of wave vector $\vec{k}$ and energy $E_k = \frac{\hbar^2 k^2}{2m^*}$ with QD (via the Coulomb potential), it loses energy and momentum resulting in the new values of $\vec{k}'$ and $E_{k'}$, while the QD electron is excited from E_1 to E_2 or E_3 (or higher) level, and then can get out of or tunnel out of QD, giving the contribution to the device current. Fig.4b illustrates the resultant effect of multiplication of carriers, producing the avalanche gain. It should be noted here, that, in contrast to the "classical" impact ionization across the energy band gap, in case of QW's and QD's, studied here, only one type of carriers (electrons, in our case) is created, so that the positive feedback of impact ionizing holes is eliminated. This leads to possibility of a rather quiet avalanche with small excess noise. For replenishment of electrons in QD's, impact ionized by incident hot electrons, Ohmic contacts are provided to the channel region to constantly supply the electrons in QD's.

The QD impact ionization process, can be understood on the base of expession for the energy dependent ionization coefficient β out of QW obtained by B.E.Levine et. al. [3]

$$\beta(E_k) \equiv E^{-2}{}_K (1 - \frac{\Delta E}{E_k})^{1/2} \quad (1)$$

In our case $\Delta E = E_n - E_1$, (n=2,3…) is the energy gained by QD in the result of interaction with the incident hot electron. The saturation of the drain current after the second step in Fig.3, can be explained according to (1) by the avalanche gain saturation at high voltages due to the reduction in $\beta(E_k)$, when $E_k > \Delta E$.

It was found out, that for the effective realization of the observed QD impact ionization, responsible for the anomal I-V-dependence, the optimal ratio between the electron populations in the ground state and in the excited states of QD's should be kept. This is needed for creation of the primary hot electrons, required for subsequent initiation of the impact ionization. The threshold field for impact ionization, which is determined by the value of the ground state energy

$E_1$of electron in QD's, can be evaluated from the I-V-C's: F_{th}=4V·μm^{-1}. Proceeding from the effect of electron emission out of QD's, we have evaluated the depth of the energy levels $E_{QD} \cong E_1$ in QD's: $E_{QD}=e \cdot F_{th} \cdot d_{QD}$ =120÷160meV, where d_{QD}=30÷40nm is the lateral size of QD's.

QD-MODFET

Using the structures S1, MODFET's with gate length of 0,4μm have been fabricated. The I-V-C's of these QD-MODFET's are shown in Fig.5. As seen from this Fig., applying even the zero-bias to the gate leads to the essential shift of the second current step to the lower voltages as compared with the "ungated" devices. This effect is associated with increasing the peak electric field under the gate. The saturation current I_{dss} for the second step practically does not depend on the gate bias U_G. However, its threshold voltage U_{th} is very effectively influenced by negative values of U_G. This is principally different from the behaviour of the "classical" FET, for which only the electron density and, respectively, I_{dss} are influenced by U_G. These results show, that in QD-MODFET's the concentration of electrons, participated in the current flow, becomes independent on U_G, but threshold voltage U_{th} for the electron emission out of QD's is reduced, when U_G becomes more negative. The reduction of U_{th} is explained by increasing the effective electric field in the d_{GD}-spacing. Therefore, the gate electrod in QD-MODFET mainly controls the electron emission out of QD's, while the density of emitted electrons is kept approximately constant. The important result of this study is the finding of the sufficiently high value of the transconductance $g_m \cong$500mS/mm at the small expected effective device capacitance.

CONCLUSION

High electric field electron transport in QD-system was studied and new QD-MODFET has been demonstrated. Its operation is principally different from that of conventional ("classical") FET, in which U_G carries out the function of the modulation of the thickness of the conducting channel. On the other hand, in QD-MODFET, at small electric fields, majority of electrons are confined in QD's. At high fields the gate-potential controls the electron emission out of QD's. The operation of such a transistor reminds that of the vacuum triod, where the gate electrod, similar to the grid electrod in vacuum triod, controls the electron emission out of their source - self organized ensemble of QD's.

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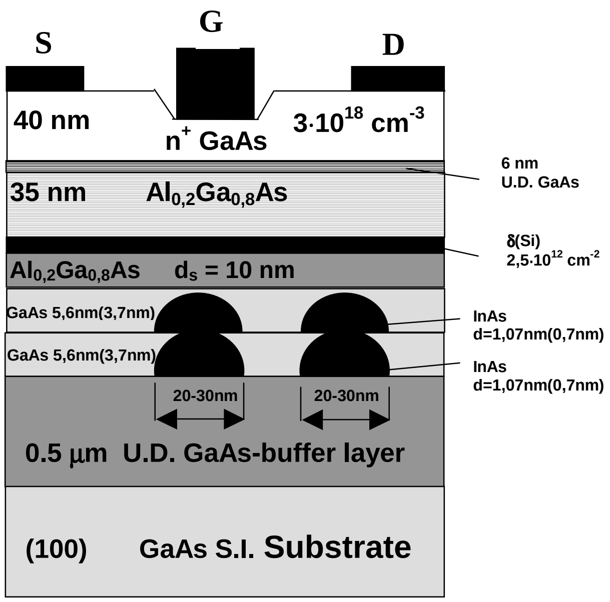

Fig. 1 Cross section of QD-MODFET structure.

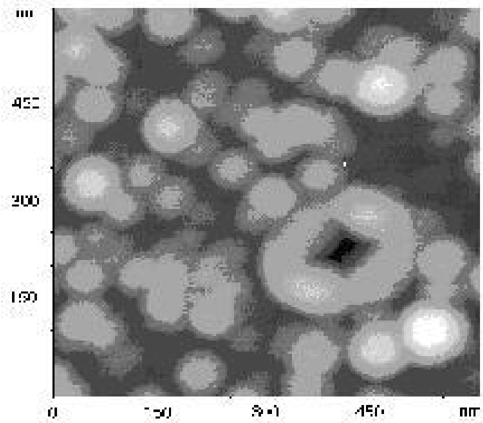

Fig. 2 AFM-photograph of sample S1.

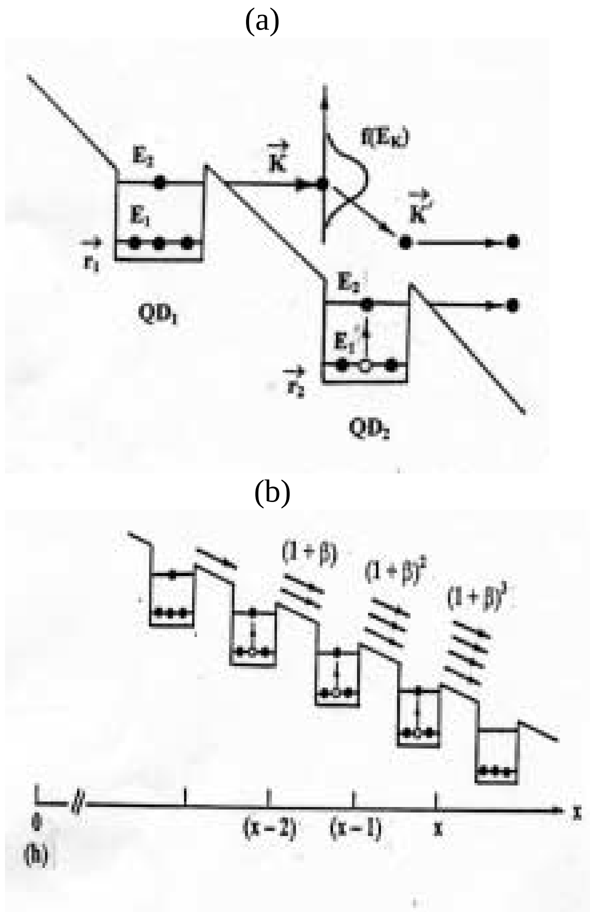

Fig. 4. (a) Schematic energy diagram showing the tunneling escape of the QD-excited state electron having momentum k→, energy E_k and the distribution function f (E_k), and the subsequent impact ionization. (b) Impact ionized electrons producing avalanche gain along the device channel.

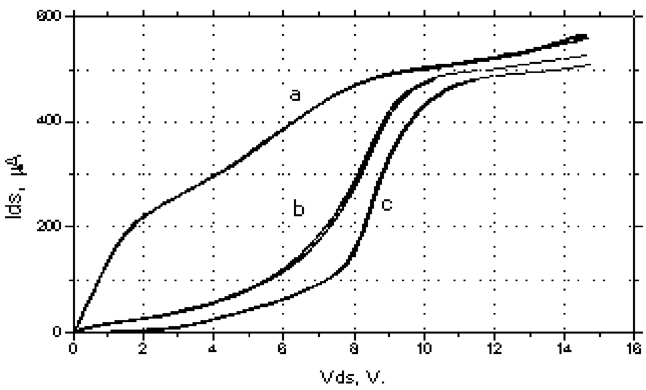

Fig. 3. I-V-characteristics of QD-MODFET structures: a- before etching, b, c- after additional surface etching.

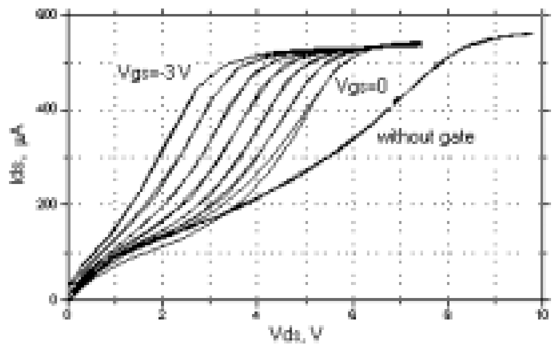

Fig. 5. I-V-characteristics of QD-MODFET structures for different values of Vg (step=-0.5V)