MOLECULAR BEAM EPITAXY OF MODULATION DOPED N-AlGaAs/(InAs/GaAs)/GaAs SUPERLATTICES AT THIKNESS OF InAs LAYERS BELOW AND NEAR THRESHOLD OF NUCLEATION OF QUANTUM DOTS FOR HIGH FREQUENCY APPLICATIONS

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ABSTRACT

Modulation doped N-AlGaAs/GaAs/InAs/GaAs/InAs/GaAs-heterostructures with InAs-quantum dots have been grown and investigated. Their photoluminescence spectra and electrical 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 quantum dot FET's present the new type of the hot electron devices, promising for high frequency applications.

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 have attached a wide 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 a critical thickness to form very small dot structures (~20nm) [1-3]. 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 very high electric field, and on the operation of the real QD-modulation doped field effect transistors (QD-MODFET's). In this work, we study the optical and electrical transport properties of the two dimensional (2D) electrons in the modulation doped N-AlGaAs/GaAs-heterostructures with the InAs-dots embedded in the GaAs-channel, and analyzed the characteristics of QD-MODFET's fabricated on their basis. It was shown that mobility μ_{2D} and concentration n_{2D} of electrons are strongly influenced by the presence of QD's. The high field I-V-characteristics (I-V-C's) of MODFET's exhibit the contributions both from mobile 2D-electrons and the electrons localized in QD's. In contrast to conventional MODFET's, QD-devices demonstrate the new type of the hot electron transistors which can be promising for high frequency applications.

MBE GROWTH OF QD MODFET-STRUCTURES

Two types of QD-MODFET-structures (S1 and S2) have been grown by molecular beam epitaxy (MBE) on (100)-semi insulating GaAs-substrates. Fig.1 shows schematically their cross sections. First we grew a 0,5μm-thick undoped GaAs-buffer layer and the two very thin InAs-layers, separated by the undoped GaAs spacer layer. For samples S1, thickness of each InAs layer was 1,07nm and thickness of the GaAs spacer layer was 5,6nm. For samples S2, these thicknesses were 0,7nm and 3,7nm, respectively. In both cases two layers of QD's with different size and density were formed. Then, after growth of the second GaAs-spacer layer with thickness of 5,6nm and 3,7nm for samples S1 and S2, respectively, the 10nm-thick undoped $Al_{0,2}Ga_{0,8}As$ spacer layer, a $2,5\cdot 10^{12}cm^{-2}$ Si δ-doped layer and a 35nm-thick undoped

$Al_{0,2}Ga_{0,8}As$ barrier layer were grown. The QD-MODFET-structures were completed by the 6nm-thick undoped GaAs layer and the 40nm-thick $3\cdot10^{18}cm^{-3}$ Si-doped GaAs contact layer. Fig 2 depicts the energy diagram of the above QD-MODFET-structures. As a reference sample (SR), 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.

OPTICAL AND ELECTRICAL PROPERTIES OF QD-MODFET-STRUCTURES

Fig 3 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 ~40nm and $3\cdot10^{10}cm^{-2}$, respectively. In Fig.4 PL-spectra of the different samples, measured at 77K, are presented. Two PL peaks in the sample RS, typical of the modulation doped quantum wells [4], correspond to the optical transitions between the two populated electron subbands and the hole subbands. On the other hand, the broad PL-bands in samples S1 and S2 correspond to the InAs-QD's. In Table 1 the results of the Hall effect measurements of mobility μ_{2D} and concentration $n_{2D}$of samples S1, S2 and SR are presented. As seen, the insertion of QD's into the device channel results in the reduction of μ_e both for sample S1 and S2, and the essential reduction of n_{2D} in sample S1. In the latter case, obviously, the trap of majority of electrons by QD's takes place. In sample S2, grown with the smaller QD-material, the lateral size of QD's can be smaller and their electrons energy levels can be shallower. As a result, the smaller number of electrons should be trapped by QD's. The low values of electron mobilities in samples S1 and S2, as compared with sample SR, are the direct indication, that insertion of InAs-QD's gives rise the specific random potentials, which scatter 2D-electrons very effectively. The charges of electrons trapped by QD's and the effects of strain around each QD can be responsible for these potentials.

HIGH FIELD ELECTRIC TRANSPORT IN QD MODFET-STRUCTURES

Because the essential part of electrons in samples S1 and S2 are trapped by QD's, they can not participate in the low field electric transport. However, their contributions can be displayed at high electric 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.5. As seen from this Fig, in contrast to "standard" FET's, they have the anomalous "two-step" shape (instead of the conventional curve with "saturation"). When the distance between the sample surface and the channel is reduced by means of etching, the first current step is reduced or even completely disappeared, and I-V-C becomes of the threshold type, due to presence of second step only. The two current steps are explained by the contributions from two types of electron states: the mobile 2D-electrons (as in "standard" FET) responsible for the first step, and the electrons localized in QD's. The second ones, responsible for the second step, give the contribution only at the high electric field F, above some threshold value, as a result of the field induced electron emission from QD's. The reduction of the current at the first step, after the additional surface etching (the surface field induced depletion) supports our interpretation of this part of I-V-C.

QD-MODFET'S

Using the structures S1 and S2, 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. 6. As seen from this Fig, applying 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 can be explained by the redistribution of the electric field in the device channel. Really, since the majority of electrons in sample S1 are

localized in deep QD-levels, and their concentration practically is not influenced by the gate bias, the potential distribution along the length of the gate should be constant. In this case, the majority of the drain – to-source voltage will drop only on the interval d_{GD} between the gate edge and the drain. Since d_{GD} is much smaller, than the source – to-drain spacing d_{SD}, the electric field F in the real working region (~d_{GD}) will be much higher, than the average F of the "ungated" MODFET. As a result, the threshold voltage U_{th} should be shifted to the lower voltages, as compared with the "ungated" devices. As seen from Fig.6, 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 result 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 a case of QD-MODFET's, the concentration of electrons participated in the current flow, becomes independent on U_G, but threshold voltage U_{th}, needed for initiation of the electron emission from QD's, is reduced, when U_G becomes more negative. This reduction of U_{th} can be explained by increasing the effective electric field in the d_{GD}-interval. The threshold field, which is determined by the energy of electron states in QD's, can be evaluated from the I-V-C's of the "ungated" MODFET: $E_{th}=4V\cdot\mu m^{-1}$. Proceeding from the effect of electron emission from QD's, we can evaluate the depth of the energy levels E_{QD} in QD's: $E_{QD}=e\cdot E_{th}\cdot d_{QD}$ =160meV, where d_{QD}=40nm is the lateral size of QD's. The important result of this study is the finding of the sufficiently high value of the transconductance $g_m\cong$500mS/mm at the very small expected effective device capacitance.

CONCLUSION

In conclusion, it should be noted that the QD-MODFET's , studied here, demonstrate the principally new RF-devices as compared with the "classical" FET's. This QD-device presents the new type of the hot electron transistor which can be very promising for the high frequency applications.

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Table 1. Results of the Hall effect measurements of μ_{2D} and n_{2D}

Samples	μ_{2D}, cm^2/VS		N_{2D}, cm^{-2}	
	77K	300K	77K	300K
SR	10108	4500	$8{,}2\cdot10^{11}$	$9\cdot10^{11}$
S1	3000	2852	$1\cdot10^{11}$	$6\cdot10^{10}$
S2	1500	1000	$8{,}3\cdot10^{11}$	$8{,}05\cdot10^{11}$

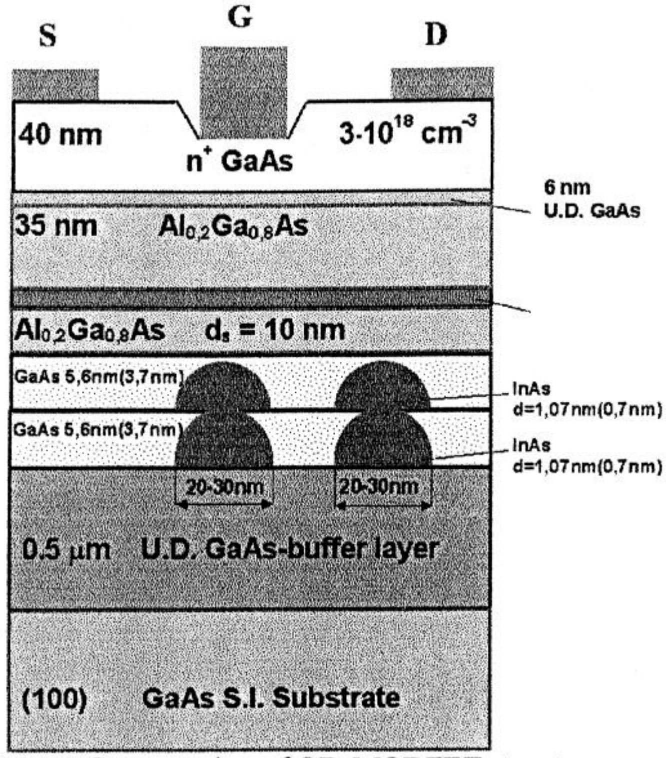

Fig. 1 Cross section of QD-MODFET structure

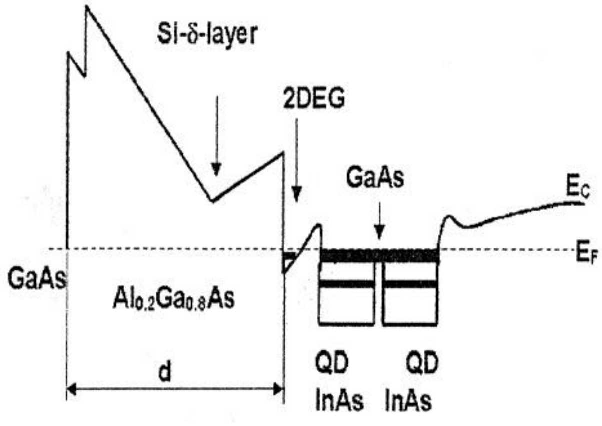

Fig. 2 Band diagram of QD-MODFET structure

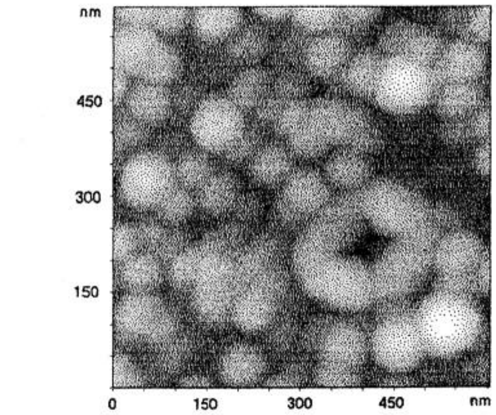

Fig. 3 AFM-photograph of sample S1

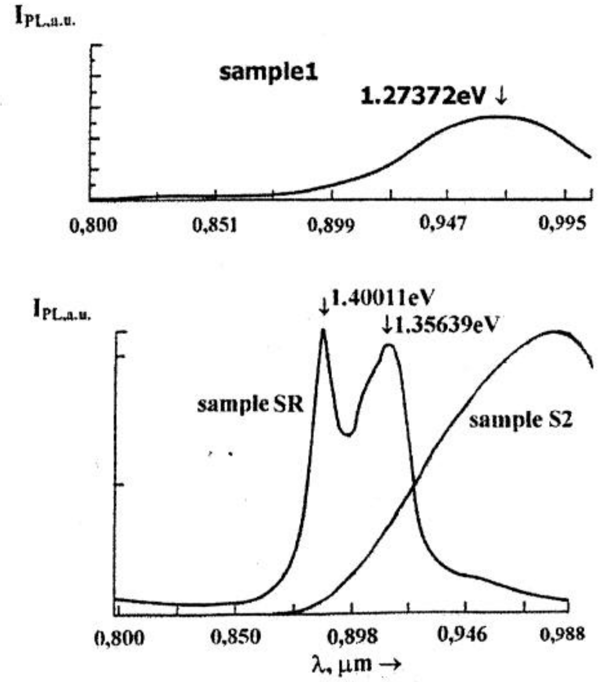

Fig. 4 PL-spectra of samples S1, S2, SR

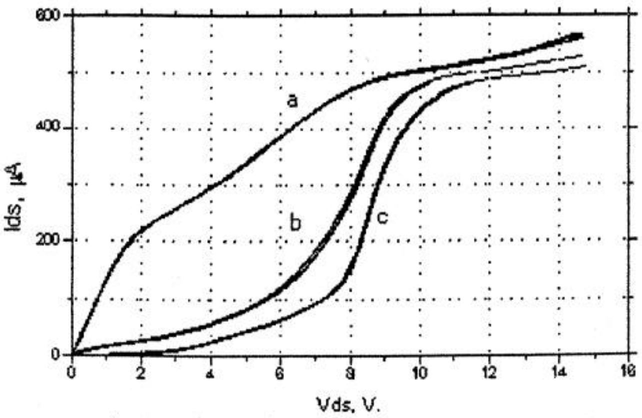

Fig. 5 I-V-characteristics of QD-MODFET structures: a- before etching, b, c- after additional surface etching

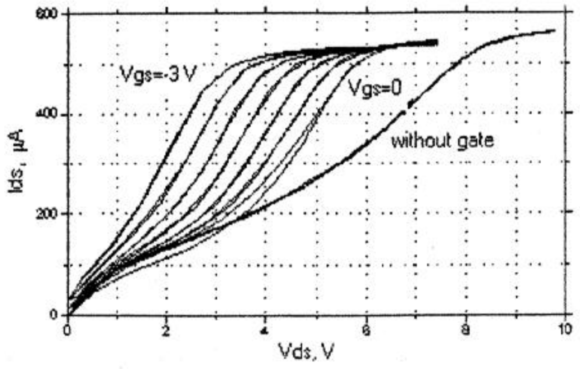

Fig. 6 I-V-characteristics of QD-MODFET structures for different values of Vg (step=-0.5V)