Self-aligned enhancement-mode and depletion-mode GaAs field-effect transistors employing the δ-doping technique

E. F. Schubert,[a] J. E. Cunningham, and W. T. Tsang

AT&T Bell Laboratories, Holmdel, New Jersey 07733

This work describes a self-aligned Schottky-gate field-effect transistor (FET) which uses the δ-doping technique during crystal growth by molecular beam epitaxy. In this new FET the δ-doping concepts are employed in three ways: (i) for the highly doped surface to obtain nonalloyed ohmic contacts, (ii) to decrease the parasitic resistances, and (iii) for the electron channel below the gate. A two-dimensional electron gas in a V-shaped quantum well is formed by the δ-doped electron channel. The advantage of nonalloyed ohmic contacts allows us to use a new two-mask, self-aligned FET process to further reduce the parasitic resistances. Both enhancement-mode and depletion-mode δ-doped GaAs field-effect transistors are fabricated. The measured transconductance of the δ-doped field-effect transistor is 240 mS/mm and is comparable to values obtained from selectively doped heterostructure transistors of the same geometry.

An abundance of new concepts for Schottky-gate field-effect transistors (FET's) arose since the advent of the two-dimensional electron gas (2DEG) in III-V semiconductor heterostructures.[1-6] These new concepts for FET's include, for example, high-mobility heterostructures,[7-10] semiconductor-insulator-semiconductor FET's,[11,12] and quantum well transistors.[13,14] Lattice matching of heterostructures, as required for devices with minority carriers, is not mandatory for majority-carrier devices such as FET's[15] thus making available a wide variety of materials. Experimental transconductances for depletion-mode selectivity-doped heterostructure transistors (SDHT's) of the frequently used $Al_x Ga_{1-x} As$/GaAs material system are typically 180–250 mS/mm at $T = 300$ K and for a gate length $\geqslant 1$ μm.[16-19]

A two-dimensional electron gas has been achieved not only in these heterostructures, but also in GaAs homostructure by the use of the δ-doping technique.[20-22] This technique allows us to localize the impurity atoms in one atomic monolayer of the host GaAs material, thereby generating a V-shaped quantum well. Even though the mobility of the δ-doped planes drops with increasing doping concentration, the 2D *conductivity*, $qn_{2DEG}\mu$, increases steadily.[22,23] Therefore, the δ-doping technique allows us to increase the mobility and conductivity beyond their respective values obtained by conventional *three-dimensional* doping procedures.[23] The potentially high performance of such FET's using a δ-doped channel has been demonstrated recently.[22] In this letter we describe a new type of homostructure FET which uses the δ-doping technique exclusively; i.e., (i) for nonalloyed ohmic contacts,[20] (ii) to decrease the parasitic resistances, and (iii) for the 2DEG as an electron channel. A self-aligned, two-mask process is used for device fabrication.

The basic structure of the FET is shown in Fig. 1. The sequence of layers epitaxially grown by molecular beam epitaxy (MBE) consists of a δ-doped electron channel with a two-dimensional donor concentration of $N_D^{2D} = 2$–6×10^{12} cm^{-2}, a series of δ-doped sheets ($N_D^{2D} = 1 \times 10^{13}$ cm^{-2},

$\mu = 2000$ cm^2/V s) separated by 20 Å and a series of six highly doped planes ($N_D^{2D} = 5 \times 10^{13}$ cm^{-2}) for nonalloyed ohmic contact formation.[20] Typical contact resistances found here are in the 10^{-6} Ω cm^{-2} range, again confirming our earlier work. Titanium (500 Å) and gold (1500 Å) are deposited in an evaporator immediately after the sample is removed from the ultrahigh vacuum MBE system. The first photolithographic step defines the active mesas, by etching (i) the Au, (ii) the Ti, and (iii) the GaAs. The height of the GaAs mesa is 0.1 μm. The second photolithographic step defines both the source and drain contacts, as well as the gate electrode. The Ti/Au contact is etched through the photoresist gate window to separate the mesa into source and drain contact. Thereupon, the gate recess[24,25] follows with wet chemical etching and an etching depth of 300–500 Å. Finally, the gate metallization (Ti/Au) is formed by a lift-off process. The self-alignment of Schottky-gate and ohmic electrodes by one single mask is made possible by elimination of the thermal annealing of the ohmic contact. Thus, a separation of ohmic and Schottky contacts of < 0.25 μm (see Fig. 1 for illustration) can be achieved with this two-mask process.
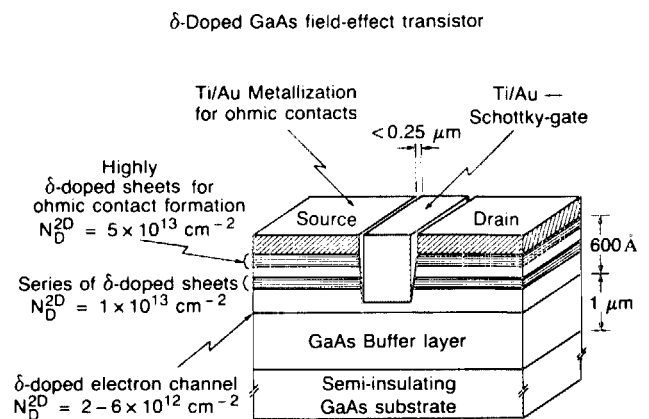
δ-Doped GaAs field-effect transistor

FIG. 1. Basic structure of the self-aligned δ-doped GaAs FET. Three δ-doped regions are used for nonalloyed ohmic contacts (top), to decrease the parasitic resistances (middle), and for the electron channel (bottom).

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[a] On leave from Max–Planck-Institut Für Festkörperforschung, Stuttgart, Federal Republic of Germany.

The energy-band diagram below the gate of a depletion-mode δ-doped FET is shown in Fig. 2 for both zero bias (a) and negative pinch-off voltage (b). The donor plane of concentration, N_D^{2D}, is located at a distance z_D away from the Schottky barrier of height, ϕ_B. One part of the electrons originating from the donor occupies surface states at the metal-semiconductor interface, while the remaining part forms the 2DEG. The threshold voltage[26] of a δ-doped FET can be determined to be

$$V_{PO} = \phi_B - (z_D/\epsilon)qN_D^{2D} , \qquad (1)$$

where the quantum size effect is neglected and the condition of validity is limited to long gate lengths. Equation (1) shows that for an appropriate choice of the distance z_D and doping concentration N_D^{2D} the pinch-off voltage can be < 0 or $\gtrsim 0$, corresponding to the depletion and enhancement-type FET operation. In a *conventional, homogeneously doped* metal-semiconductor FET (MESFET) the pinch-off voltage depends quadratically on the channel depth z according to

$$V_{PO} = \phi_B - [z^2/(2\epsilon)]qN_D . \qquad (2)$$

Clearly, this quadratic dependence makes the threshold voltage control more sensitive to the etching depth as compared to the linear dependence of the δ-doped FET inferred from Eq. (1). Therefore, the threshold-voltage control in a δ-doped FET is superior to conventional MESFET's.

The enhancement-mode operation of a δ-doped FET is shown schematically in Figs. 2(c) and 2(d) for the off-state (zero bias) and on-state (positive gate voltage), respectively. Enhancement-type operation of the δ-doped FET can be achieved with either a lower doping concentration, or a reduced distance z_D as indicated in Fig. 2(c). Practically, we determine the pinch-off voltage during the recess etch by simultaneously monitoring the source-drain current and stopping the etching at an appropriate drain current. Both types of FET's have a gate recess of *less* than 600 Å which is relatively shallow[25] and results in improved controllability of the gate recess. Figure 3 shows experimental current-voltage (I-V) characteristics of an enhancement-mode FET, including the source-gate Schottky characteristic [Fig.
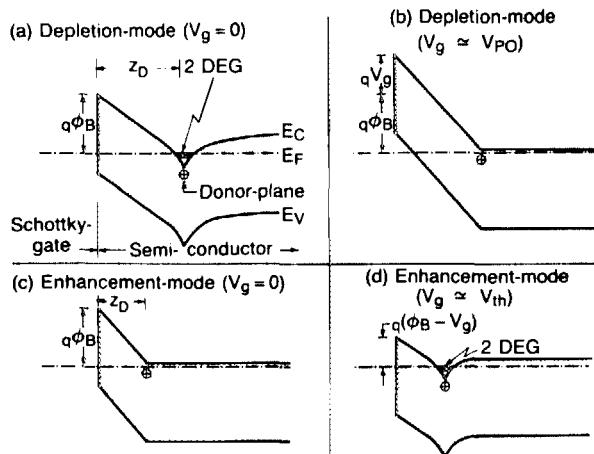

FIG. 3. Gate-source (a) and drain-source (b) current-voltage characteristics of a δ-doped enhancement-mode FET with $L_g = 1.3\,\mu$m and $W_g = 150\,\mu$m. The gate voltage is $+ 0.7$ V for the top drain current trace.

3(a)] and the drain-source I-V traces ($L_g = 1.3\,\mu$m, $W_g = 150\,\mu$m, $V_{th} = -0.3$ V). The turn-on voltages of the gate diodes are typically 0.8 V. The output characteristic [Fig. 3(b)] shows excellent pinch-off and a small output conductance in the saturation regime. The transconductance of the FET shown in Fig. 3 is 153 mS/mm.

In addition to enhancement-mode FET's, depletion-mode δ-doped FET's were fabricated with gate lengths of 1.3 μm (nominal length of 1 μm). Experimental results of the source-gate I-V characteristics and of the output characteristic are shown in Figs. 4(a) and 4(b), respectively. The depletion-mode FET's have excellent pinch-off characteristics and a small output conductance in the saturated regime. The extrinsic transconductance of the δ-doped FET is 240 mS/mm. To the best of the authors' knowledge, this transconductance is among the highest ever reported for *homostructure* GaAs FET's employing the same device geometry. Both depletion-mode and enhancement-mode FET's have a relatively high gate breakdown voltage of $V_b < -5$ V, typically -10 to -15 V. The origins of the high breakdown voltage are the *linear* potential drop between gate and channel[22] and the absence of doped material between gate and channel. Furthermore, we also do not observe any threshold voltage shift which is desirable for applications in integrated circuits.

In conclusion, a new Schottky-gate GaAs homostructure FET has been fabricated by using the δ-doping technique during the growth by molecular beam epitaxy. Nonal-

FIG. 2. Energy-band diagram of a δ-doped depletion-mode FET at zero gate-voltage (a), and at pinch-off (b), as well as of an enhancement-mode δ-doped FET at zero bias (c), and at positive gate voltage (d).
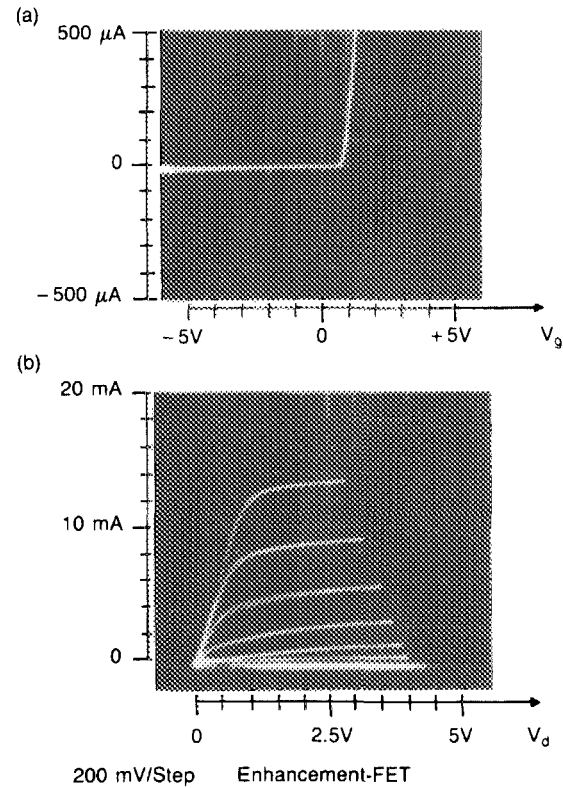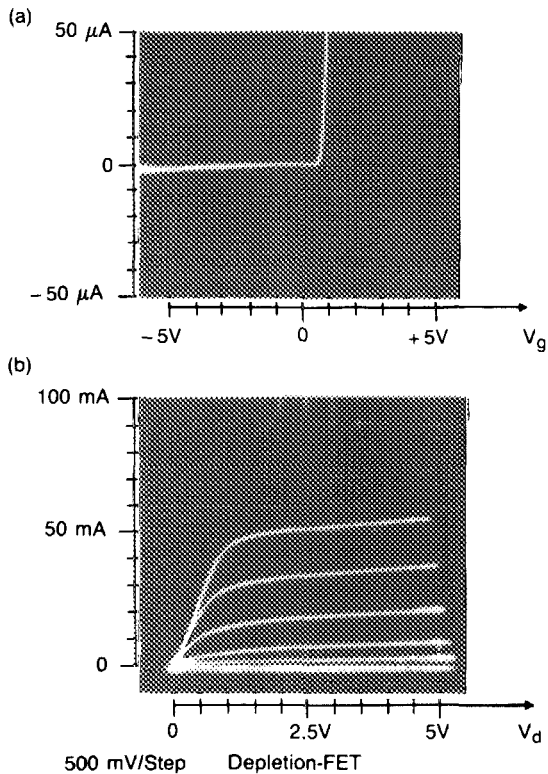
FIG. 4. Gate-source (a) output (b) current-voltage characteristics of a δ-doped depletion-mode FET with $L_g = 1.3$ μm, $W_g = 150$ μm, and $g_m = 240$ mS/mm. The gate voltage is $+ 0.5$ V for the top drain current trace.

loyed, δ-doped ohmic contacts are used for source and drain contacts. The two-dimensional specific resistance of the epitaxial layer is below 50 Ω. Enhancement-mode and depletion-mode FET's with high gate-breakdown voltage are realized. The threshold-voltage control of the δ-doped FET is shown to have theoretical advantages when compared to conventional MESFET's. A measured transconductance of 240 mS/mm for a depletion-mode FET with a gate length of 1.3μm is achieved, which is comparable to the transconductance obtained with SDHT.

The authors would like to thank T. H. Chiu and M. D. Feuer for helpful discussions, and J. A. Ditzenberger for technical assistance.

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