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Characterization of AlGaN/GaN high frequency transistors with field-plate electrode on a silicon substrate

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The electrical breakdown and microwave characteristics of AlGaN/GaN transistors with different field-plate electrodes, electrically connected to the source via a common bus, were studied. It was shown that adding field-effect electrodes increases the breakdown voltage, increases the gain by more than 2 dB in the frequency range up to 15 GHz.

Keywords: field plate, gallium nitride, GaN, power RF HEMT, breakdown voltage, maximum stable gain (MSG).

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1. Introduction

Currently, microwave transistors with high electron mobility (HEMT) based on AlGaN/GaN heterostructures are actively used in a wide range of technical systems from household radio stations to mobile communication base stations. The price of transistors and microcircuits becomes decisive in mass production. In this regard, the direction of epitaxial growth and lithography technologies on silicon substrates with diameters of 150 and 200 mm is actively developing. The task of developing new transistor designs to increase the operating voltage to values > 50 V, and improve low-frequency and high-frequency parameters has also become urgent. One of the approaches to its solution is the use of additional field electrodes (field plate) [1]. A field electrode electrically connected to the gate lowers and smoothes the maximum in the distribution of electric field strength from the drain side [2,3], increasing the breakdown voltage and suppressing current collapse. Also, the use of a field electrode improves the temperature stability of the transistor [4]. The simplest way to manufacture a field electrode with a minimum of technological operations is to change the shape and widen the „hat" of the T-shaped gate [5]. But this increases the gate-drain and gate-source capacitances, causing a decrease in gain and transconductance, thereby affecting the overall high-frequency characteristics of the transistor. To simultaneously improve frequency response and breakdown voltage, the field electrode and gate are separated in the active channel area and electrically connected via a common bus. At the same time, the optimal geometry corresponding to the maximum breakdown voltage [2] can be selected for each electrode.

In this paper, we studied the dependence of the maximum operating voltages and microwave parameters of gallium nitride transistors on the presence (absence) and design of an additional field electrode electrically connected to the source via a common bus. All transistors were manufactured in a single process cycle on a silicon substrate. Electronic lithography was used for the manufacture of T-shaped gates.

2. Theoretical assessment of breakdown stresses

The distribution of the electric field and the occurrence of breakdown in an AlGaN/GaN HEMT with a T-shaped gate and various field electrode designs have been studied using mathematical modeling. The parameters of the barrier layer ($Al_{0.27}Ga_{0.73}N$ with a thickness of 20 nm) were selected based on the need to ensure high microwave output power. The geometry of the electrodes was determined by the available manufacturing technology. Drain–source distance — 4 μm, gate length — 0.25 μm, width — 100 μm, length „hat" gate — 0.8 μm, height of the „foot" of the gate — 100 nm, height of the „hat" — 200 nm. The considered HEMT structures are shown in Figure 1: a simple T-gate (FP0), a discrete field electrode (FP1), and a field electrode with an overlapping T-gate (FP2). Unlike the transistor design discussed in Refs. [2,3], the field electrode is electrically connected to the source via a common bus outside the channel area. A photo of the appearance of the transistor with the FP2 design is shown in Figure 1. During manufacture, transistors are passivated with a layer of plasmochemical silicon nitride covering all structural elements. The thickness of the dielectric between the field electrode and the barrier layer of the heterostructure is 300 nm.

The field electrode creates additional capacity. To maintain good frequency characteristics, this capacity should not exceed 10–15 % of the initial capacity of the T-shaped gate. Using the model of a flat capacitor between a metal electrode and a two-dimensional electron gas for a rough estimate of the capacitances, we obtain the maximum length of the field electrode $0.58-0.86\,\mu$m. The length of the field electrode was chosen to be 0.8 mm for the convenience of optical lithography in the manufacture of the transistor. The distance between the field electrode and the gate is selected to be $1\,\mu$m in order to avoid premature surface breakdown during experiments.

The simulation was carried out using the Sentaurus TCAD computer-aided design (CAD) system. The piezoelectric constants of the materials were taken from Ref. [6]. The charge transfer was calculated using the drift-diffusion model. Deep impurities were accounted for using a single acceptor carbon level with an ionization energy of 0.9 eV [7], described in the framework of the Shockley-Reed-Hall model. Carbon is the predominant impurity with a concentration of $10^{17}\,\mathrm{cm}^{-3}$, which completely compensates for the donor admixtures of oxygen and silicon during the growth of the instrument heterostructure. During the simulation, the shock ionization coefficients for electrons and holes in GaN were set by an empirical law:

$$\alpha_{n,p} = \alpha_0 e^{-eE_{br}/|\nabla F_{n,p}|}$$

with the adjustment parameters [8] obtained from the measurement of photomultiplication in a reverse-biased diode:

	α_n	α_p
α_0, cm^{-1}	$2.69 \cdot 10^7$	$4.32 \cdot 10^6$
E_{br}, V/cm	$2.27 \cdot 10^7$	$1.31 \cdot 10^7$

$F_{n,p}$ is the quasi-Fermi level for electrons and holes.

For each point of the line along the length of the transistor structure from the source to the drain, the maximum value of the electric field strength in the cross-sectional plane of the two-dimensional electron gas region and the barrier layer at a drain voltage of 200 V was calculated. The corresponding distribution is shown in Figure 2. It can be seen from the graph that the electric field strength is maximum near the T-gate foot. Avalanche generation of carriers begins in this place and an electrical breakdown occurs as a result with a further increase in voltage. The addition of an additional field electrode to the transistor design reduces the maximum value of the electric field strength near the T-gate foot by 25 % from 7.9 to 5.9 MV/cm. The local maximum of tension at the edge of the T-gate hat practically disappears and moves to the edge of the field electrode. The maximum electric field strength of the drain is also reduced by 10 % from 6.6 to 6.0 MV/cm. Using the definition of the breakdown voltage from Ref. [3], its increase from 240 to 280 V was shown. At the same time, the type of field electrode does not have a special effect on the breakdown voltage. This is because changing the design of the field electrode only changes the position and, to a lesser extent, the absolute value of the local maximum electric field strength at the edge of the electrode.

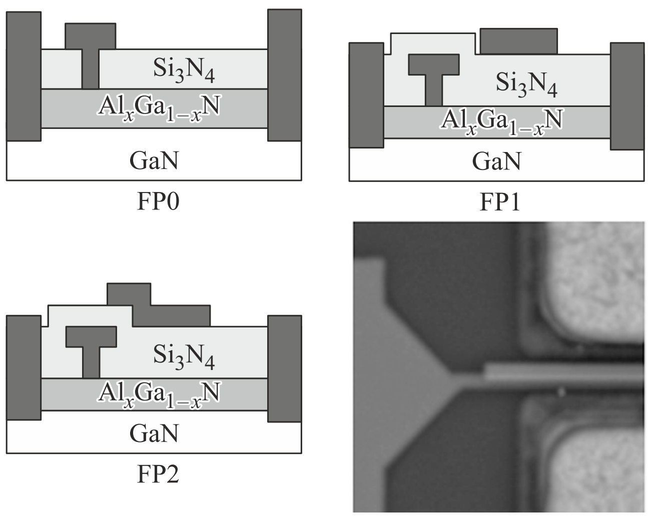

Figure 1. Schematic cross-section of the studied GaN HEMT and a photograph of the appearance of the test transistor with FP2 design.

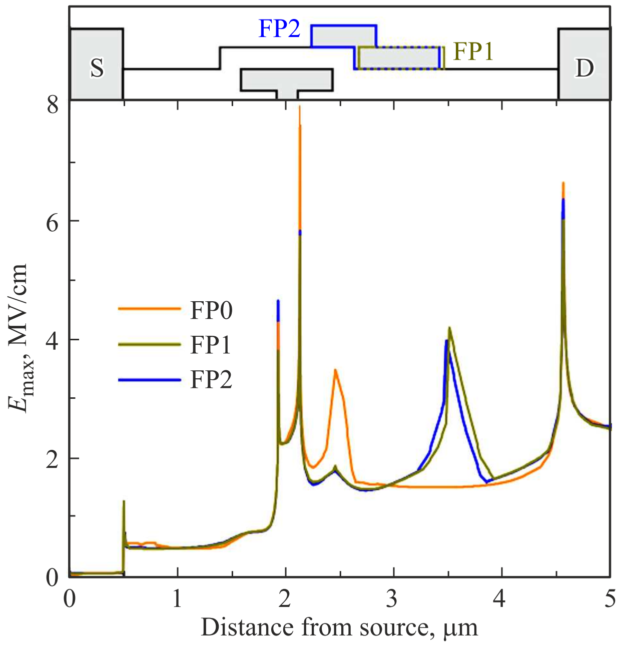

Figure 2. The dependence of the maximum value of the electric field strength in the cross-sectional plane of a two-dimensional electron gas region and a barrier layer on the distance between the cross-sectional plane and the source.

3. Measurement of leakage currents and transistor degradation voltage

12 technological modules with the same topology were manufactured to estimate the spread of transistor parameter values on the plate. Each process module consists of two transistors with a T-gate without field electrodes (FP0),

Table 1. Leakage currents (I_L) and degradation voltage (V_{DEG}) of test transistors

№	I_L, μA				V_{DEG}, B			
	FPO		FP1	FP2	FPO		FP1	FP2
1	6	5	15	12	150	140	180	160
2	3	x	15	29	180	180	220	225
3	20	40	60	x	180	180	200	200
4	50	30	50	20	60	100	100	100
5	x	2	15	2	200	160	200	210
6	x	x	100	90	100	20	140	100
7	3	3	2	2	200	220	280	290
8	5	6	x	2	180	200	180	230
9	5	3	x	10	150	180	x	250
10	100	60	100	100	150	100	190	200
11	15	2	x	3	200	190	280	270
12	x	x	2	2	270	220	280	340

one transistor with a discrete field electrode (FP1) and one transistor with a field electrode overlapping the T-gate (FP2). The cut-off voltage of the manufactured transistors is practically independent of the presence (absence) and design of the field electrode and is -3 V. The leakage current I_L on the drain of closed transistors was measured at a gate voltage of -5 V and a drain voltage of 140 V. The experimental conditions were selected to test the threefold reliability margin of the operating voltage of 50 V. The leakage current is practically the most important parameter for high-power microwave transistors, along with the saturation current, which determines the output power range and operating voltage of the transistor. Usually, the drain voltage must be maintained at a third of the breakdown voltage for safe and reliable operation.

The measurement results are presented in Table 1. The symbol „x“ means that the drain current of the test transistor significantly exceeds 100 μA or 1 mA/mm of gate width, the value corresponding to the occurrence of an electrical breakdown of drain$-$source, gate$-$drain, gate$-$source of the transistor.

By counting the number of „x“ symbols, the yield of functional transistors can be estimated based on the breakdown voltage. 10 non-functional test transistors out of 48 means the ~ 80 % yield of functional transistors, which shows a good maturity of manufacturing technology and high quality heterostructure. No statistically significant advantage of the additional field electrode and no noticeable effect on the leakage current level (I_L) in the drain$-$source breakdown mode are seen from Table 1. The minimum current values of $2-3\,\mu$A are achieved on all types of transistors, the average values are comparable and lower for transistors without field electrodes.

It can be seen from Figure 2 that the distribution of the electric field has pronounced maxima at the drain and gate. To study avalanche generation in the diode switching mode, a reverse voltage was applied between the gate and the drain before the transistor degradation (irreversible current growth) began. The gate of the transistor melts and burns out during degradation. A photo of the melted gate is shown in Figure 3. The degradation voltage (V_{DEG}) of each transistor was recorded and presented in Table 1. Most of the values are less than the theoretical limit obtained from the calculations in sec. 2. This may be due to both unintentional doping of the instrument structure with donor impurities (Si and O), the presence of structural defects, and an underestimation of the shock ionization constants used in calculations.

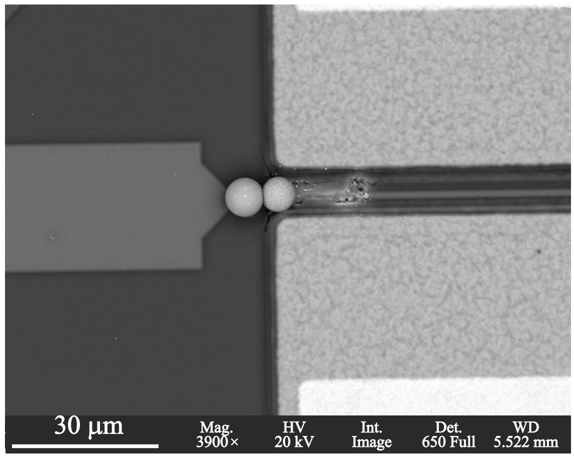

Figure 3. Transistor gate after measuring an irreversible increase in drain current.

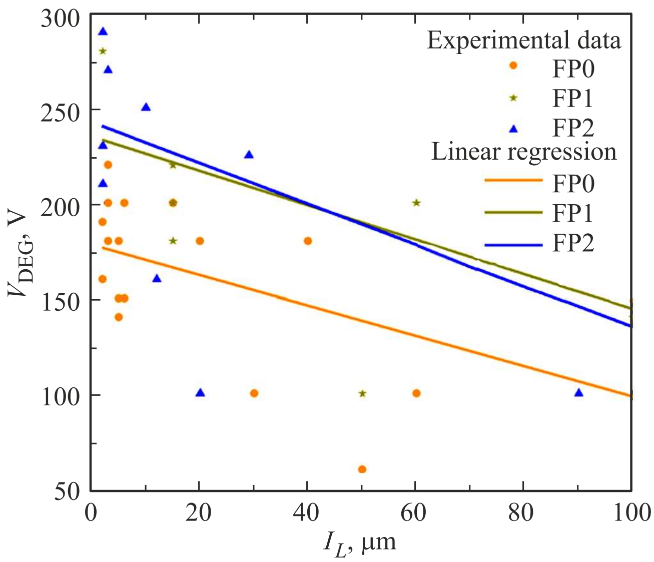

Figure 4. The dependence of the burnout voltage on the leakage current of the transistor.

All transistors are marked with dots in the parameter space in Figure 4 (leakage current I_L, burnout voltage V_{DEG}). A general trend can be identified, with high leakage currents, the burnout voltage decreases. The corresponding regression lines are shown in Figure 4. Thus, the amount of leakage current can be used as a control parameter when disassembling transistors. However, it should be borne in mind that all transistors with leakage currents < 1 mA per millimeter of gate width are susceptible to degradation in different ways. In particular, a lower value of I_L should be used for sampling to obtain reliable instruments.

A comparison of the regression lines shows that the addition of a field electrode to the transistor design leads, on average, to an increase in the degradation voltage by 40–60 V over the entire range of leakage currents, which is consistent with the calculation results. The average value $V_{\rm DEG}$ for transistors without a field electrode (FP0) is 162 V, for transistors with a discrete field electrode (FP1) — 204 V, for transistors with an overlapping gate and field electrode (FP2) — 214 V. Thus, it is necessary to use a field electrode to create a margin of reliability for manufacturing transistors with an operating voltage of > 50 V.

4. Measurement of microwave parameters

To carry out the microwave measurement, the transistors in question were scaled and manufactured with a two-finger gate with a width of $2 \times 125\,\mu$m. All other design parameters have not been changed. This gate topology is more convenient than a single-finger one for microwave measurements due to its symmetry and agreement with the design of the microwave probes. Figure 5 shows the results of measurements of flow characteristics and steepness at a drain voltage of 28 V. The addition of a field electrode changes the maximum steepness and saturation current by less than 5 %. The cut-off voltage is practically unchanged.

The operating points for measuring low-signal microwave parameters are selected near the maximum ransconductance and are shown in Figure 5 with the symbol „asterisk“. The measurements were carried out on a measuring stand based on the Keysight PNA-X N5244B vector circuit analyzer and Amcad AM3200 switching power supplies under the control of the Amcad IVCAD measurement management software environment. The dependences of the maximum stable gain (MSG) on frequency shown in Figure 6 were constructed. The graph shows that the addition of a field electrode to the transistor design increases MSG by more than 2 dB in the frequency range up to 15 GHz.

During subsequent measurements using the load pull method, the output power, gain, and efficiency of the drain at a frequency of 5 GHz were estimated. Input power 15 dB, drain voltage 28 V. The results are shown in Table 2. For a test transistor without a field electrode, the average specific value of the maximum output power is 5.55 W/mm, with an efficiency of 60 %, gain is 16.5 dB. The measured values

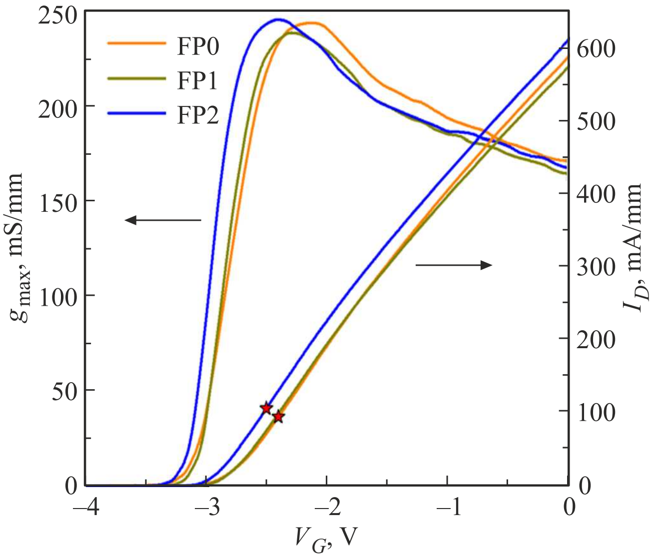

Figure 5. Saturation current and steepness of the test transistor.

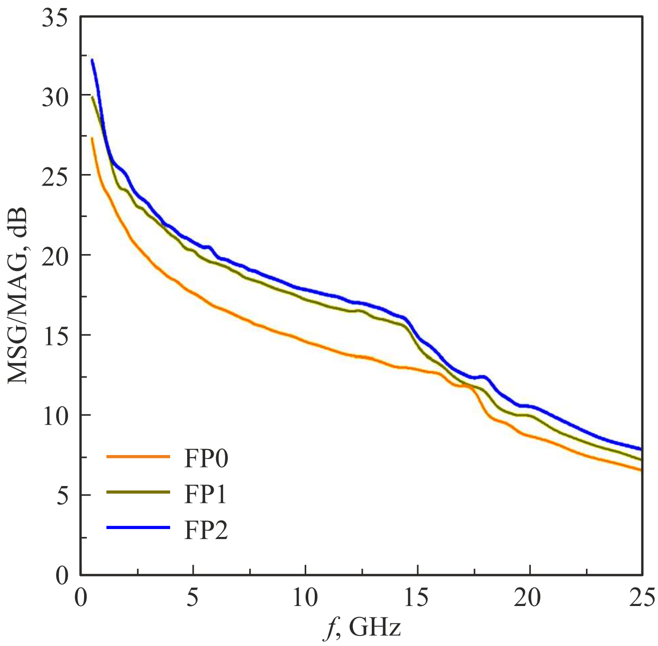

Figure 6. Maximum stable gain of test transistors.

for field-effect electrode transistors differ from those given by no more than 10 %, including the spread of parameters across the plate.

To explain the weak influence of the field electrode on the measured characteristics, the nominal values of the elements of the low-signal equivalent circuit HEMT [9] without a field electrode (FP0) and with a discrete field electrode (FP1) in the maximum gain (maximum steepness) mode were calculated. The values are given in Table 3. R_g, R_s, R_d is the gate, source and drain resistances determined from measurements of the transistor in passive mode ($V_d = 0$ V, $V_g = 0$ in); C_{gs}, C_{ds} is the gate capacity–source, drain–source; C_{dg} is the

Table 2. Measurement results using the active load method

	FP0	FP1	FP2
Output power, W/mm	5.55	5.37	6.11
Efficiency, %	59.67	59.59	60.49
Gain factor, dB	16.42	16.28	16.84

Table 3. Parameter values of the equivalent transistor circuit

Type of transistor	R_g, Ohm	R_s, Ohm	R_d, Ohm	G, mS	C_{gs}, pF	C_{dg}, pF	C_{ds}, pF	R_{ds}, Ohms	I_{ds}, mA	f_t, GHz	$G_{\max}$ (10 GHz), dB
FP0	3.4	3.8	5.7	87	0.543	0.035	0.08	853	155	25	14.6
FP1	3.4	3.5	5.7	90	0.592	0.021	0.136	746	73	23	16.7

feedback capacity, primarily affects the maximum gain $G_{\max}$; R_{ds} is a parameter that determines the resistance of an open channel.

It follows from Table 3 that field-effect electrode transistors have a slightly higher internal ransconductance at a low microwave signal (360 mS/mm versus 350 mS/mm) and a maximum gain (16.7 dB at 10 GHz), but a slightly lower boundary frequency f_t. The addition of a field electrode electrically connected to the source increased the capacitance of C_{gs} by 10 %, which confirms the applicability of the used in sec. 2 simplified models of a flat capacitor for estimating its capacitance. As a result, we get that the capacitance C_{dg} on field-effect transistors is smaller, and the capacitance C_{ds} is larger, which, in our opinion, compensates for the increase in low-signal gain on a large signal. This is also indicated by a slight decrease in the boundary frequency.

5. Conclusion

The dependences of the maximum operating voltages and microwave parameters of AlGaN/GaN HEMT on a silicon substrate on the presence (absence) and design of an additional field electrode electrically connected to the source via a common bus are studied in this paper. It is found that an additional field electrode significantly increases the breakdown voltage before degradation. It must be used to create a margin of reliability for operating voltages of 50 V and above. There were no noticeable differences in the microwave parameters of the large signal of transistors with and without a field electrode, and no improvements or impairments were detected. Therefore, to operate at relatively low operating drain voltages up to 25 V, in order to simplify the technology and reduce the cost of manufacturing the device, additional manufacturing operations for the field electrode may not be performed.

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Conflict of interest

The authors declare that they have no conflict of interest.

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