Comparison of AlGaN/GaN MSM Varactor Diodes Based on HFET and MOSHFET Layer Structures

M. Marso, A. Fox, G. Heidelberger, P. Kordoš, and H. Lüth

***Abstract*—In this letter, the performance of AlGaN/GaN-based metal–semiconductor–metal (MSM) varactor diodes based on HFET and MOSHFET layer systems is investigated. Passivated HFET MSM devices are coated with a 10-nm-thick SiO_2 layer between the electrodes; in MOSHFET-based diodes, this layer is also used as an insulator underneath the gate. Device fabrication uses standard HFET fabrication technology, allowing easy integration in monolithic microwave integrated circuits. Devices with different electrode geometry are characterized by direct current and by S-parameter measurements up to 50 GHz. The HFET-based varactors show capacitance ratios up to 14 and cutoff frequencies up to 74 GHz. The MOSHFET-based devices, on the other hand, show lower capacitance ratios and poorer stability because of the insulation layer between electrodes and semiconductor.**

***Index Terms*—Gallium nitride, metal–insulator–semiconductor (MIS) devices, metal–semiconductor–metal (MSM) devices, metal–oxide–semiconductor heterojunction field-effect transistors (MOSHFETs), modulation-doped field-effect transistors (MODFETs), varactors.**

I. Introduction

The metal–semiconductor–metal diode above a two-dimensional electron gas (MSM-2DEG) has shown its potential as a varactor that can be easily integrated with HFET devices [1]–[3]. This possibility of monolithic integration is especially important in the AlGaN/GaN material system where alternative integration methods, such as selective epitaxy, are not mature [4]. Furthermore, the capacitance swing of this varactor diode based on an HFET layer structure is much larger than for conventional varactor diodes. In addition, the capacitance swing can be tuned by the electrode geometry in contrast to conventional p-n, Schottky, or heterostructure diodes where the ratio is only defined by the layer structure [5], [6]. Shortly after the development of the AlGaN/GaN MOSHFET with reduced gate current, the MSM-2DEG based on this layer structure was proposed as a radio frequency switch [7]. In this letter, we compare the varactor properties of MSM-2DEG devices based on the HFET (HFET MSM) as well as on the passivated HFET (pass. HFET MSM) and the MOSHFET layer system (MOSHFET MSM) (Fig. 1, inset).

The MSM-2DEG diode consists of two back-to-back connected Schottky diodes above a 2DEG layer structure. Its electrical behavior is analyzed in detail in [2]. The capacitance of the unbiased MSM-2DEG is determined by the electrode area and by the distance to the 2DEG channel that acts as an equipotential plane. An applied bias voltage depletes the channel below the reverse-biased electrode. For large bias voltages, the depletion region penetrates deeply into the device, and the capacitance drops to a very low value within a small voltage range. The transition voltage V_{TRANS} from high to low capacitance depends on the 2DEG carrier density and is strongly related to the threshold voltage of the corresponding transistor. In fact, the threshold voltage of the transistor is the gate-to-source voltage, where the channel is completely depleted. Because the MSM-2DEG consists of two back-to-back connected gate electrodes, V_{TRANS} is the threshold voltage of the reverse-biased contact added by the voltage drop at the forward-biased contact.

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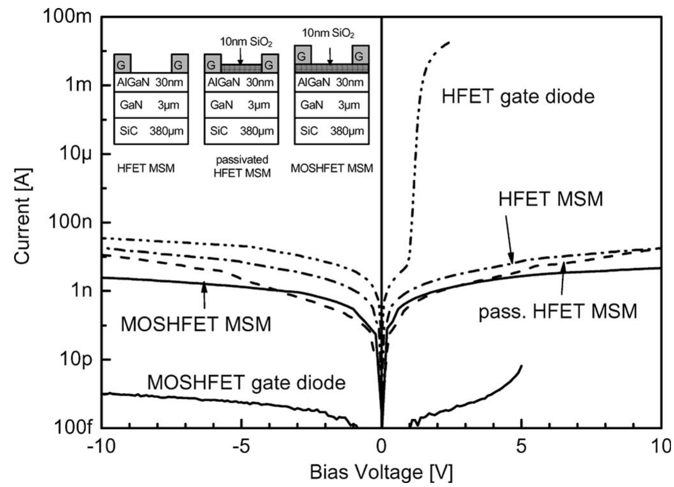

Fig. 1. DC characteristics of the MSM-2DEG devices (electrode length = 2 μm, spacing = 1 μm) and of the reference gate diodes (area = 25 × 25 μm^2). Inset: layer system and schematic diagram of the investigated devices. G: gate electrode.

II. Experiment

The HFET layer stack was grown by metal–organic vapor phase epitaxy on semiinsulating SiC substrate by Cree-GaN Durham. For optimal comparability, all devices emanate from the same wafer consisting of a SiC substrate, a 40-nm-thick AlN nucleation layer, a 3-μm GaN layer, and a 30-m $Al_{0.28}Ga_{0.72}N$ layer. Room temperature Hall measurements yield a 2DEG carrier concentration of 7.1×10^{12} cm^{-2} and a mobility of 1835 $cm^2/V \cdot s$. The MSM-2DEG diodes are fabricated simultaneously with transistor devices to prove the absolute compatibility with HFET technology. The device processing starts with mesa insulation performed by argon sputtering, followed by Ti/Al/Ni/Au ohmic, contact pad, and Ni/Au gate metallization, as described previously [8]. A SiO_2 layer with a nominal thickness of 10 nm is deposited by plasma-enhanced chemical vapor deposition at 300 °C before gate metallization for the MOSHFET-based devices and after gate fabrication for the passivated HFET-based diodes (Fig. 1, inset). The two-finger gate electrodes are defined by electron beam lithography. Unless otherwise stated, the electrode dimensions are 50, 2, and 1 μm for finger width, length, and separation, respectively. Gate diodes consisting of a large gate electrode with 25×25 μm^2 area and an ohmic contact are fabricated as reference. These reference diodes are prepared without contact pads that are needed for the much smaller MSM-2DEG devices.

III. Results and Discussions

Fig. 1 shows the direct current behavior of MSM devices and of reference gate diodes based on the HFET and the MOSHFET layer structures. The HFET gate diode shows a typical Schottky diode characteristic with a reverse current in the 10–50-nA region and a forward current that increases from 10 nA to 1 mA in a bias range from 1 to 1.5 V. Because the MSM-2DEG consists of two gate diodes connected back-to-back, the forward current of the forward-biased diode of the MSM-2DEG is identical to the reverse current of the reverse-biased contact. Therefore, the applied bias voltage drops mainly across the reverse-biased contact, minus the well-defined voltage drop of 1–1.2 V across the forward-biased diode. Application of the SiO_2 passivation layer does not change the characteristics of the HFET gate diode. However, it reduces the current of the MSM-2DEG device. We attribute the different behavior to the reduction of surface currents between the contact pads of the MSM-2DEG device.

The MOSHFET reference gate diode shows essentially the leakage current through the insulation layer. For the MOSHFET MSM device, the current is governed by the leakage current through the buffer layer between the contact pads that connect the gate electrodes on the mesa with the buffer layer. The (although low) buffer conductivity creates a parasitic resistance in the gigaohm range parallel to each MOSHFET gate diode. The current through this parallel resistance is several decades larger than the intrinsic MOSHFET gate current. This behavior has a large impact on the device performance because the voltage distribution between forward- and reverse-biased diode is governed by the parasitic parallel resistances rather than by the intrinsic diodes. This results in a more or less symmetric voltage distribution affected by the different geometries of the contact pads, by the pad-to-semiconductor resistances, by the contribution of parasitic surface currents, by the trap influence in the buffer, etc. Obviously, the relation between the bias voltage and the voltage drop of the reversely biased contact of the MOSHFET MSM is not as well defined as for the HFET MSM diode.

The capacitance–voltage (*C–V*) characteristics are evaluated by two-port S-parameter measurements up to 50 GHz by an HP Network Analyzer 8510C. A π-network is determined by the

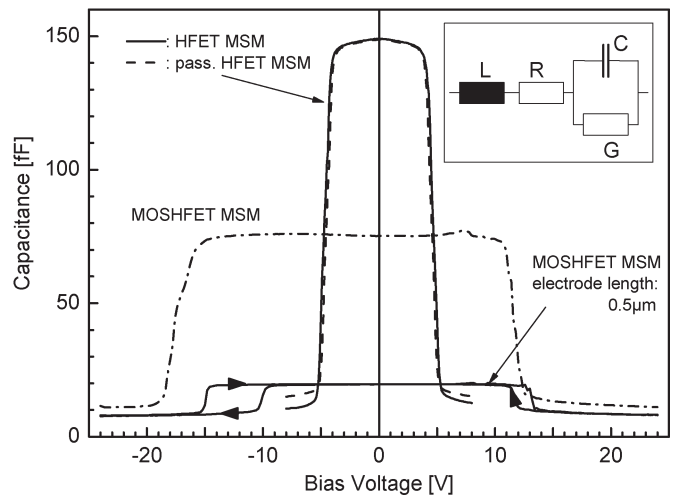

Fig. 2. Capacitance–voltage (*C–V*) characteristics of the investigated devices. Electrode length and spacing are 2 and 1 μm, respectively, unless otherwise noted. Inset: varactor equivalent circuit.

S-parameters, with the parallel elements as contact pad parasitics and the series element as intrinsic device. The measurements are fitted to an equivalent circuit model of the device in the whole frequency range from 500 MHz to 50 GHz. The exact equivalent circuit of MSM-2DEG diodes is very complex. The electrodes must be described by the transmission line model theory to consider the frequency dependence [2]. However, the measurements can be fitted to a common varactor equivalent circuit with capacitance C, parallel conductance G, series resistance R, and inductance L when the frequencies are not too high (Fig. 2, inset). This equivalent circuit is valid in the whole measurement frequency range for the investigated electrode layouts. Even the parallel conductance can be neglected for the investigated structures.

Fig. 2 shows the *C–V* relationship of the MSM-2DEG devices. The capacitance of the HFET MSMs is nearly constant up to the transition voltage of 5 V, which corresponds to the threshold voltage of -4.1 V for HFET transistors in this layer system [8], added by the voltage drop of 1 V of the forward-biased diode (Fig. 1). The capacitance of the unbiased device corresponds well with half the value of a plate capacitance with the area of one electrode and with the 30-nm-thick AlGaN layer as dielectric [2]. The capacitance of one electrode with length and width of 2 and 50 μm, respectively, and a relative dielectric constant of 9.5 is 280 fF. Above the transition voltage where the reverse-biased electrode has completely depleted the 2DEG channel, the capacitance drops below 10 fF within a small voltage range. The HFET MSM with passivation layer shows nearly the same behavior. Only the high-voltage capacitance is larger because of the higher parasitic capacitance by the passivation layer. Table I gives a summary of the varactor data of the investigated devices. The cutoff frequency f_0, which is defined as $f_0 = [2\pi C(0\ \mathrm{V}) R(0\ \mathrm{V})]^{-1}$, can be increased from 31 to 74 GHz by reducing the electrode length and spacing. The observed increase of the series resistance with reduced electrode length is described by the transmission line model [2].

The capacitance characteristics of the MSM-2DEG based on the MOSHFET structure show large differences compared

TABLE I
SUMMARY OF THE MAJOR MSM-2DEG PROPERTIES OF ALL INVESTIGATED DEVICES. THE SERIES INDUCTANCE L OF ALL DEVICES IS ABOUT 150 pH, AND THE PARALLEL CONDUCTANCE G IS ZERO

Sample	Length [µm]	Distance [µm]	C_{MAX} [fF]	C_{MIN} [fF]	C_{MAX}/C_{MIN}	R(0V) [Ω]	f_0 [GHz]
HFET	0.5	0.5	36.5	8.3	4.4	58.8	74
HFET	0.5	1	36	8	4.5	63.7	69
HFET	2	1	150	10.5	14.3	33.5	31
pass. HFET	2	1	149	14.6	10.2	33.5	32
MOSHFET	2	1	77	12	6.4	32	65

to the HFET devices: The low-voltage capacitance is lower because of the SiO_2 dielectric layer between the Schottky electrode and the semiconductor. The additional series capacitance by the 10-nm-thick SiO_2 layer with a relative dielectric constant of 3.9 is 345 fF for one electrode, resulting in a total electrode capacitance of 154 fF. The additional capacitance also increases the threshold voltage of the MOSHFET transistor from -4.1 to -9.8 V [8]. Furthermore, the characteristic is asymmetric, i.e., the transition voltage V_{TRANS} depends on the bias polarity. It even depends on the measurement direction, as depicted in Fig. 2 for a device with 0.5 μm electrode length. The origin of both asymmetry and hysteresis lies in the undetermined distribution of the bias voltage between forward- and reverse-biased contact. At the transition voltage of the MSM-2DEG, the voltage drop of the reversely biased contact is the threshold voltage of the MOSHFET based on this layer structure. The current through both reverse- and forward-biased electrodes is mainly determined by the parasitic currents through the buffer. If both parasitic parallel resistances are identical, then the voltage drop across both contacts is the same. This results in a transition voltage of the MOSHFET MSM that is twice the threshold voltage. This is in contrast to the HFET MSM, where the transition voltage is close to the threshold voltage. The parasitic parallel resistances are governed by the pad-to-semiconductor contacts and by the buffer whose defects act as carrier traps. We attribute the observed asymmetry and hysteresis to the undefined and unstable properties of these parasitic resistances. The voltage distribution between both contacts, and therefore also the transition voltage, are defined by parasitic currents in the nanoampere range (Fig. 1). Therefore, it is barely possible to fabricate MSM-2DEG diodes in the MOSHFET layer system with controllable and stable device properties.

These results show that the current reduction by the dielectric layer between gate electrode and semiconductor can improve the transistor properties, but it seriously degrades the MSM-2DEG performance.

IV. CONCLUSION

We have fabricated MSM diodes above a 2DEG based on HFET, passivated HFET, and MOSHFET AlGaN/GaN layer systems. Fabrication of these devices is fully compatible with the transistor fabrication process. HFET-based devices with and without a passivation layer show the suitability for use as varactor diodes with large capacitance ratio and transition voltages defined by the layer structure and the 2DEG properties. The MOSHFET-based devices, on the other hand, show a smaller capacitance swing, a hysteresis in the capacitance–voltage characteristics, and a transition voltage that is strongly influenced by the parasitic buffer current. Therefore, we conclude that although the MOSHFET transistor may be equal or even superior to the conventional HFET devices, MSM-2DEG varactor diodes should be fabricated without an insulation layer between gate and semiconductor to insure device performance and stability.

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