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Silicon Dioxide-Encapsulated High-Voltage AlGaN/GaN HFETs for Power-Switching Applications

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***Abstract*—In this letter, new approach in achieving high breakdown voltages in AlGaN/GaN heterostructure field-effect transistors (HFETs) by suppressing surface flashover using solid encapsulation material is presented. Surface flashover in III-Nitride-based HFETs limits the operating voltages at levels well below breakdown voltages of GaN. This premature gate-drain breakdown can be suppressed by immersing devices in high-dielectric-strength liquids (e.g., Fluorinert); however, such a technique is not practical. In this letter, AlGaN/GaN HFETs encapsulated with PECVD-deposited SiO_2 films demonstrated breakdown voltage of 900 V, very similar to that of devices immersed in Fluorinert liquid. Simultaneously, low dynamic ON-resistance of 2.43 m$\Omega \cdot$ cm^2 has been achieved, making the developed AlGaN/GaN HFETs practical high-voltage high-power switches for power-electronics applications.**

***Index Terms*—AlGaN–GaN heterostructure field-effect transistor (HFET), breakdown voltage, field plate (FP), HEMT, high-voltage power device, surface flashover.**

I. Introduction

HETEROSTRUCTURE field-effect transistors (HFETs) based on AlGaN/GaN show tremendous promise as switching elements for power-electronic applications. As common to all power semiconductor devices, achieving high breakdown voltages V_{BR} with minimum ON-resistance R_{ON} has also been the primary challenge for AlGaN/GaN HFETs. A common route taken to address this challenge in AlGaN/GaN HFETs was in optimizing the field profile in gate-drain region to sustain the highest possible operating voltage at the lowest L_{GD} value [1]–[8].

In the past, single or multiple field plates (FPs) (overlapping gate) have been implemented to increase breakdown voltages in AlGaN/GaN HFETs [2], [5], [6]. AlGaN/GaN HFET with multiple FPs demonstrated breakdown voltage of 900 V for a device with $L_{\mathrm{GD}} = 24\ \mu$m [6]. The mechanism of V_{BR} increase in FP devices is believed to be electric-field spike reduction at drain-side edge of the gate. Recent important findings show that, in HFET devices, either with or without FPs, the breakdown voltage is limited by surface flashover that occurs in air regions adjacent to gate-drain area and is not due to breakdown of III-Nitride material itself [10], [12], [13]. It has been shown that suppression of surface flashover by immersing the devices in high-dielectric-strength liquid material Flourinert results in linear V_{BR}–L_{GD} dependence, reaching breakdown voltages above 1.5 kV at $L_{\mathrm{GD}} = 20\ \mu$m. Linear V_{BR}–L_{GD} dependence by immersion in Flourinert clearly demonstrates the feasibility of achieving very high breakdown voltages in AlGaN/GaN HFETs. However, such method can hardly be considered as a practical way of fabricating devices for high-voltage power converters. Hence, it is important to find an alternative way to suppress surface flashover without the need of immersing the devices in the liquid.

In this letter, we present a detailed study of AlGaN/GaN HFET breakdown voltages with different encapsulation materials to show that high-dielectric-strength solid insulating films can be successfully used to suppress surface flashover.

II. Experimental Details

AlGaN/GaN HFETs used for this letter were grown on sapphire substrates by low-pressure MOCVD. The device epilayer structure consisted of 15-nm-thick low-temperature-grown AlN buffer layer followed by 1-μm-thick undoped GaN layer, which was capped with 25-nm $Al_{0.25}Ga_{0.75}N$ barrier layer. Device fabrication started with mesa etching, Ti/Al/Ti/Au ohmic contact deposition and annealing followed by Ni/Au gate formation. The gate length $L_G = 2\ \mu$m and gate-source spacing $L_{\mathrm{GS}} = 2\ \mu$m were kept constant, whereas the gate-drain spacing L_{GD} varied from 2 to 20 μm. The gate width was $W_G = 100\ \mu$m. The layer sheet resistance $R_{\mathrm{SH}} = 350\ \Omega/\mathrm{sq}$ and contact resistance $R_C = 1\ \Omega-$mm were measured using standard transmission-line-model procedure. The threshold voltage was $V_T = -4.5$ V, and saturation current at zero gate bias for fabricated devices was 0.6 A/mm. The device I–V characteristics are given as inset in Fig. 2(a).

III. Results and Discussion

The breakdown voltage measured using Tektronix 370A curve tracer was defined as the drain voltage at which drain–current exceeds 1 mA/mm with gate biased below threshold voltage. As-fabricated (AF) devices (unpassivated and with out FP) were tested for breakdown voltages in air and in Fluorinert ambience. As shown in Fig. 1, V_{BR}–L_{GD} curve for Flourinert ambience (open diamonds) yields a breakdown voltage of 900 V at $L_{\mathrm{GD}} = 20\ \mu$m. The corresponding ON-resistance is $R_{\mathrm{ON}} = 2.43$ m$\Omega \cdot \mathrm{cm}^2$. However, these R_{ON} values correspond to static device I–V characteristics only.

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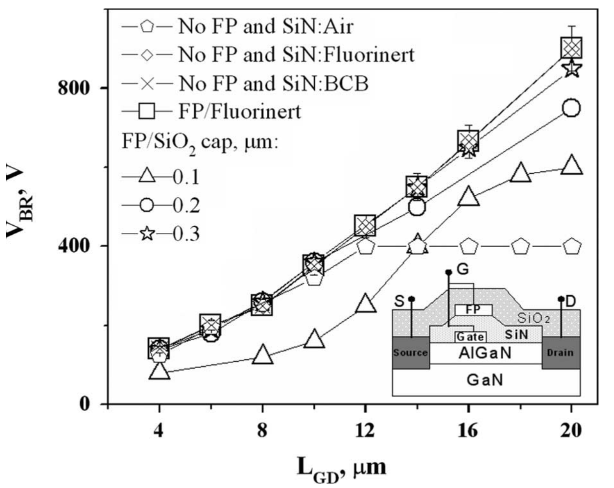

Fig. 1. $V_{\rm BR}$–$L_{\rm GD}$ dependence of AF and FP AlGaN/GaN HFETs in Fluorinert ambient and when encapsulated in varying thickness PECVD-deposited SiO_2/BCB. The inset shows schematic layout of SiO_2-encapsulated FP-HFET.

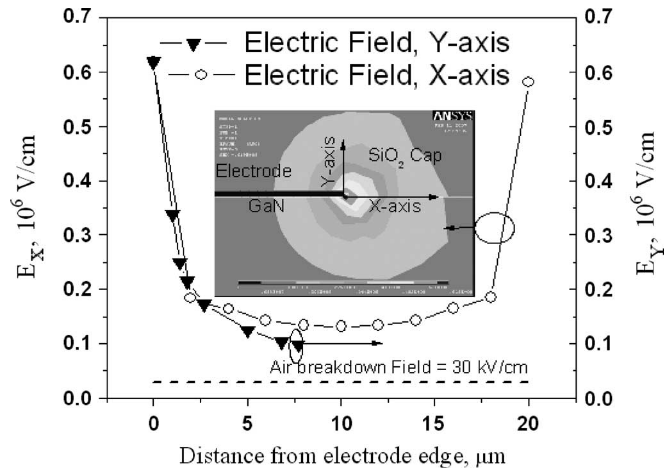

Fig. 3. Simulated electric-field distribution (in volts per centimeter) between two electrodes 20 μm apart sitting on top of GaN ($\varepsilon_r = 9$) with 25-μm $SiO_2(\varepsilon_r = 4)$ surrounding the electrodes using ANSYS. The potential difference between the electrodes is 400 V. The field along the x-axis in the figure corresponds to the field along GaN/SiO_2 boundary in the electrode plane between the electrodes and the field along the y-axis corresponds to the field along the gate/electrode edge in to SiO_2 layer.

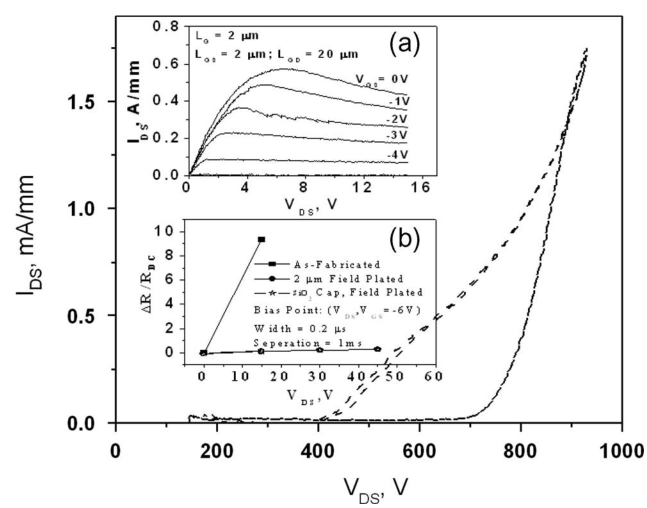

Fig. 2. OFF-state drain–current ($V_{\rm GS} = -6$ V) for a 20-μm gate-drain spacing device. The inset (a) shows dc I–V of AlGaN/GaN HFET and (b) shows relative increase in dynamic ON-resistance with respect to dc ON-resistance for AF and FP-HFETs. The dynamic ON-resistance has been measured by taking the device pulsed current–voltage characteristics immediately after application of different drain voltage pulses. A pulse width of 0.2 μs and the pulse period of 1 ms were used.

As shown in Fig. 2(b), due to large-signal dispersion (also referred to as current collapse), these AF devices have the dynamic ON-resistance, which significantly exceeds static values and, thus, cannot be used for switching applications.

In order to suppress current collapse and achieve low-dynamic ON-resistance, the devices were subsequently passivated and FP. First, 0.1-μm-thick Si_3N_4 passivation layer was deposited. Next, Ni/Au FP with 2-μm overhang toward the drain was deposited on top of Si_3N_4 passivation layer; this was connected to the gate-contact pad through an opening in passivation layer. As shown in Fig. 2(b), FP-HFETs show minimal increase in dynamic ON-resistance. The devices were then tested for breakdown voltages in Fluorinert ambient. As shown in Fig. 1, the measured $V_{\rm BR}$–$L_{\rm GD}$ data of FP-devices (open squares) were identical to those of AF devices yielding a breakdown voltage of around 900 V at $L_{\rm GD} = 20$ μm in Fluorinert.

As discussed in [12] and confirmed by devices described above, the effect of different design features on HFET switch performance can be summarized as follows. The SiN passivation mitigates current collapse and allows for low dynamic ON-resistance; however, it causes high gate-leakage currents reducing breakdown voltages to 100–200 V. FP limits this SiN-induced gate-leakage-current-increasing breakdown voltage of passivated devices. However, breakdown voltages of FP-HFETs are still limited by surface flashover. Hence, high-dielectric-strength encapsulation of FP-HFETs to suppress surface flashover is needed to achieve high-breakdown-voltage low ON-resistance performance.

For obvious reasons, solid encapsulating materials are much more preferable for practical device fabrication and packaging than liquid Fluorinert. An ideal encapsulation layer should have breakdown fields exceeding those of GaN and AlGaN (around 3 MV/cm). Among the reported materials meeting, these criteria are PECVD-deposited Si_3N_4 (3–12 MV/cm) [14] and SiO_2 (3–12 MV/cm) [15]. For presented studies, we chose silicon-dioxide films as the encapsulation material because of its low dielectric constant ($\varepsilon_r = 3.9$) as compared to that of SiN ($\varepsilon_r = 7.5$), which leads to a lower gate capacitance and, correspondingly, to lower switching losses.

One of the key parameters determining performance of HFET with solid encapsulation is the required thickness of dielectric cap layer. In order to estimate the minimal dielectric-film thickness required for effective encapsulation, we have carried out 2-D simulations using ANSYS software package of lateral and transverse electric-field distribution between two electrodes with 20-μm spacing laid out on top of GaN ($\varepsilon_r = 9$) and capped with 25-μm $SiO_2(\varepsilon_r = 4)$ film. As shown in Fig. 3, SiO_2 encapsulation layer thicker than 5 μm is needed for peak electric field around the electrodes to drop below the air breakdown field of 0.03 MV/cm for an applied potential of 400 V between electrodes.

Next, we carried out an experimental study of FP AlGaN/GaN HFETs with different thickness of encapsulated SiO_2 films. The devices were first encapsulated with 0.1-μm-thick PECVD-deposited SiO_2 film. After that, $V_{\rm BR}$–$L_{\rm GD}$ dependence was measured, and the next 0.1-μm encapsulation layer was deposited. The results for FP devices with different SiO_2 cap film thickness are compared in Fig. 1. As shown, 0.1- and 0.2-μm-thick films were not able to completely suppress the premature breakdown. However, deposition of 0.3-μm-thick SiO_2 film resulted in almost the same $V_{\rm BR}$–$L_{\rm GD}$ curve as in Fluorinert ambience suggesting aimed suppression of surface flashover by 0.3-μm SiO_2 encapsulation. A consistently high breakdown voltage of 850–900 V was measured over several 0.3-μm-thick SiO_2-encapsulated devices with $L_{\rm GD} = 20\ \mu$m in air ambience. As shown in Fig. 2(b), the SiO_2 encapsulation has no negative effect on the dynamic ON-resistance. Fig. 2 shows the OFF-state drain–current ($V_{\rm GS} = -6$ V) for 20-μm gate-drain spacing device. The devices also showed no change in the leakage current proving SiO_2-encapsulated FP AlGaN/GaN HFETs to be a strong candidate for high-voltage low-ON-resistance switches.

Note that, in our experiments, we have not observed the air flashover, although 0.3-μm SiO_2 encapsulation is certainly not thick enough to completely absorb the high-field region near gate electrode, as follows from 2-D simulations. Possible explanation of observed results is related to the mechanism of avalanche-breakdown development in air. As shown in [16], ions formed during ionization of air accelerate and hit the surface of insulating encapsulating material charging it. The charge accumulation at insulator–air interface decreases the interface field ultimately, extinguishing the plasma. As the field in plasma reduces, field inside the insulating film increases. Thus, electric field inside the insulator defines the minimum thickness of insulator required to suppress air flashover and explains observed AlGaN/GaN HFET $V_{\rm BR}$–$L_{\rm GD}$ thickness dependence.

Finally, 2–3-μm-thick cured Bisbenzocyclobutene (BCB) with high dielectric strength of 3–5 MV/cm [17] was also found to be effective in suppressing the premature gate-drain breakdown and achieving high breakdown voltages in AF AlGaN/GaN HFETs, very close to those in Fluorinert. BCB has advantages of low dielectric constant ($\varepsilon_r = 2.65 - 2.5$), low moisture intake, and simple processing. The limitation associated with BCB encapsulation is its relatively low operating temperature of 350 °C; the active-region temperature in high-power III-N HFETs can exceed this limit due to self-heating [18].

IV. Conclusion

The suppression of premature breakdown due to surface flashover in AlGaN/GaN HFETs has been achieved using PECVD-deposited SiO_2 film encapsulation. It has been found that 0.3-μm-thick film can effectively suppress the flashover for 20-μm gate-drain separation, resulting in 900-V 2.43-m$\Omega \cdot$cm^2 dynamic ON-resistance FP AlGaN/GaN HFETs. Similar high-breakdown-voltage AlGaN/GaN HFETs have been obtained using 2-μm-thick BCB film encapsulation. These results demonstrate practical approach to making high-voltage III-Nitride switching devices for power-converter applications.

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