A 36 W CW AlGaN/GaN-Power HEMT Using Surface-Charge-Controlled Structure

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Abstract — **We describe high power 36 W CW operation at 30 V using AlGaN/GaN HEMTs on SiC. Surface-charge-controlled structure, consisting of n-type doped thin GaN cap layer on AlGaN/GaN HEMT structure, is used to obtain high gate-drain breakdown voltage and to reduce current collapse. By optimizing threshold voltage of this structure, we obtained a maximum drain current of 1A/mm and a gate-drain breakdown voltage over 200 V. A 24-mm-wide-gate chip showed output power of 45.6 dBm (36 W) at 2.2 GHz with a liner gain of 9.7 dB.**

I. Introduction

AlGaN/GaN-based HEMTs are promising for microwave power applications, including L-band wireless base stations. There are many reports related to high output power density using a narrow gate device [1]. Pulsed measurements also exhibit high output power by suppressing heat generation [2]. Although continuous wave (CW) operation is required for high power application, a few papers reported total CW power over 30W using a wide gate chip [3]. This was because thermal problem occurred especially when a sapphire substrate was used. To solve a heat-sinking problem, a flip-chip or a SiC substrate has been considered. In this paper, we investigated GaN-HEMTs on SiC substrates and introduced the surface-charge-controlled structure [4], demonstrating a 36 W CW total output power.

To obtain higher RF-power and power added efficiency, we have to suppress frequency dependent characteristics, such as large transconductance (gm) dispersion, gate-lag and current collapse [5-7]. We controlled the polarization-induced surface charge by n-type doping in a thin GaN cap on AlGaN and stabilized n-GaN-surface between electrodes using strongly stressed SiN [4]. This structure exhibited high off-state and on-state breakdown voltages of 200 V and 70 V with a maximum drain current of 1 A/mm. Recently, AlGaN-thickness effect began to be discussed [8]. In this paper, we studied the effect of threshold voltage (Vth) on drain current, BVgd and current collapse to obtain high output power with high

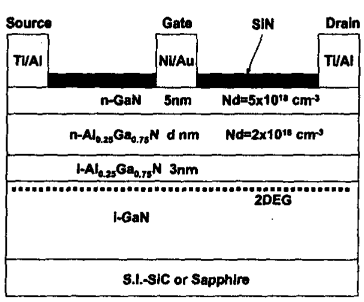

Fig.1. Schematic drawing of investigated surface-charge-controlled n-GaN-cap structures. Thin n-type GaN cap layer was grown on AlGaN/GaN conventional structure. Al mole fraction is 20-25%. SiN passivation was formed on GaN cap layer between electrodes. N-AlGaN thickness was varied to control Vth.

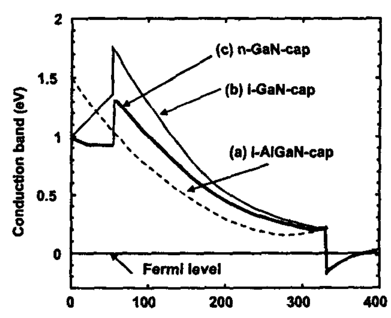

Fig. 2. Simulated band structure of (a) conventional AlGaN cap structure, (b) un-doped GaN cap structure and (c) novel surface-charge-controlled structure with thin n-GaN cap layer. N-GaN layer is 5 nm thick.

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efficiency using surface-charge-controlled structure.

II. EXPERIMENTAL

Figure 1 shows the device structures investigated (using in-house MOVPE grown Ga-face material on SiC substrates). N-AlGaN thickness was varied to change Vth. Mesa etching is used for isolation. Source/drain and gate electrodes were Ti/Al and Ni/Au. A stepper is used for gate lithography. Typical gate length is 0.9 µm. A strongly stressed SiN was deposited on the n-GaN cap layer using plasma CVD after forming a gate electrode. Then, an air-bridged HEMT chip is fabricated. Gate width (Wg) was varied from 40µm to 24 mm. After air-bridge fabrication, a 24-mm-Wg chip was wire-bonded into a package with capacitors to obtain good impedance match.

II. RESULTS AND DISCUSSION

A. Surface-Charge-Controlled Structure on Sapphire

Figure 2 shows typical band diagram of the surface-charge-controlled structure (the n-GaN cap layer on $Al_{0.20}Ga_{0.80}N$/GaN HEMTs) compared with conventional structures. The surface-charge-controlled structure screens the polarization charges at GaN/AlGaN interface by 25% as shown in Fig.2 [4]. The conduction band in the near surface region is almost flat compared with the un-doped GaN cap case. Several researchers investigated un-doped thin GaN cap layers to decrease gate leakage by the effect of piezoelectric and spontaneous polarization at GaN/AlGaN interface [9]. Maximum drain current was, however, low compared with the conventional structures due to reduced channel charge. In addition, it is relatively difficult to obtain good ohmic contact for un-doped thin GaN cap layer. Here we suppress the surface charge effect on AlGaN and can obtain good ohmic contact with the n-type doped thin GaN cap layer.

Figure 3 shows off-state gate-drain breakdown voltage (BVgd-off) as a function of maximum drain current (Imax) when sapphire substrates were used. Compared with a conventional AlGaN-cap structure, the surface-charge-controlled n-GaN-cap structure showed higher BVgd-off of 140 V, defined as a Vgd at a gate current of 500 µA/mm. N-GaN cap also screened surface traps.

B. Surface-Charge-Controlled Structure on SiC

We compared three different thick n-AlGaN layers to control Vth as shown in Table I. We controlled Vth from -9 V to -2 V by changing AlGaN thickness. Structure A and B exhibited BVgd-off of 160-200 V, When Vth became to -9 V (Structure A), however, BVgd-off is less than 10 V. We introduced Ig measurement when Vgd is

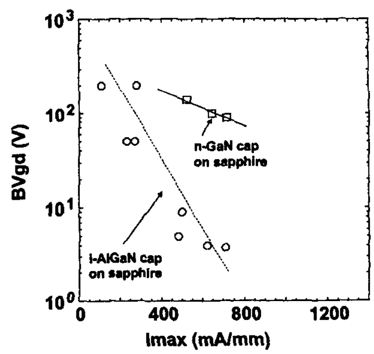


Fig. 3. Off-state breakdown voltage (BVgd-off) as a function of maximum drain current (Imax) when sapphire substrates were used.

TABLE I
SUMMARY OF DC CHARACTERISTICS

Structure No.	A	B	C
Vth (V)	-9	-5.5	-2
Idss at Vg=0 V (mA/mm)	980	750	300
Imax at Vg=2 V (mA/mm)	1200	1000	450
Gm-max (mS/mm)	150	180	230
BVgd1(V) at Igd=500 µA/mm	7.5	>200	160-200
BVgd2 (V) at Igd=1 mA/mm	50	>200	160-200
Ig -pinched-off (µA/mm) at Vgd=Vth	810	60	25
Ig (µA/mm) at Vgd=-50 V	1000	90	65

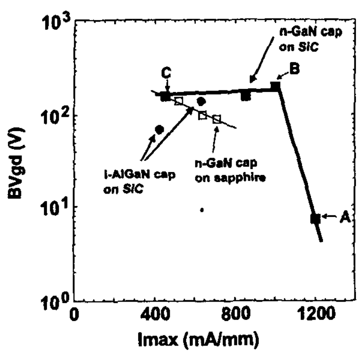


Fig. 4. BVgd as a function of Imax. The effect of cap structures and substrates were investigated. Results of surface-charge-controlled N-GaN cap structures A, B, and C in Table I were also shown in this figure.

settled to Vth (Table1). Gate leak current at Vgd of Vth increased, when Vth became negative. This is attributed to larger leakage through Schottky barrier till the 2DEG channel becomes pinched off state. This indicates that there is a limit of Vth even if the surface-charge-controlled structure is used. Imax decreased at structure C, suggesting that structure C with Vth of –2 V is not sufficient for high power operation even if gm is large.

Figure 4 shows the dependence of BVgd-off on maximum drain current. When n-GaN cap was used with SiC substrates, we could obtain high BVgd with high drain current. BVgd for SiC is larger compared with that of sapphire, suggesting that SiC is more promising to achieve high BVgd.

C. DC and RF Characteristics (Wg=40-80 μm)

Figure 5 shows I-V characteristics measured by a 100 Hz curve-tracer. We compared the characteristics among different Vth of surface-charge-controlled structure. When Vds was around 20 V, no current collapse was observed. When Vds was around 50 V, however, current collapse occurred only for structure C (most positive Vth). Only structure B showed high Imax and high BVgd without current collapse. This suggests that current collapse occurred when Vth became positive. Electron depletion thickness from surface may play an important role of current collapse.

Figure 6 shows transconductance (gm) as a function of Vgs. DC-gm and RF-gm were compared to discuss gm dispersion. For structures A and B, DC-gm and RF-gm are almost same at the gm peak region, indicating that gm dispersion was suppressed by *n*-GaN cap layer. However, around Vg of 0 V, RF-gm is larger than DC-gm. This is mainly attributed to heat generation produced by high current density around 1A/mm. For structure C, DC-gm and RF-gm are the same at all Vgs. This is due to lower current density.

E. Power Characteristics (Wg=24 mm)

Figure 7 shows power characteristics at 2.2 GHz as a function of Vds. Structure B and C were to estimate the effect of Imax and current collapse on power characteristics. We could operate 24-mm-Wg HEMTs at 30 V. CW total output power increased till 30V without grinding a 400-μm-thick SiC substrate. We obtained saturation power (Psat) of 36 W at 30 V for structure B. P1dB was over 30 W at 30 V. Psat for structure C is 2 dBm lower than structure B, which consistent to the difference of Imax

Figure 8 shows CW power measurement results at 30 V.

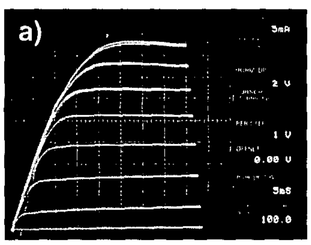
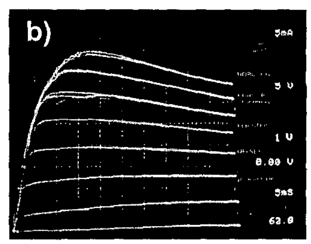
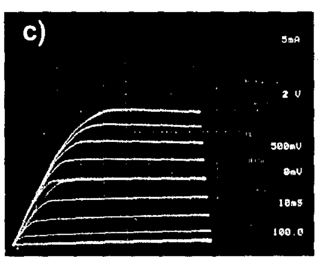
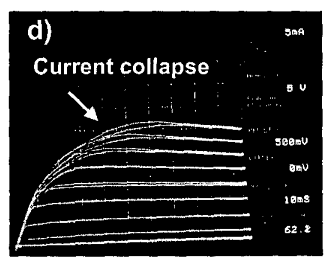
	Vds = 17 V	Vds=50 V
Structure B		
Structure C		

Fig. 5. Summary of Ids-Vds characteristics of two different surface-charge-controlled structures B and C. A gate width is 40μm. Vertical division is 5 mA. Horizontal division is 2 V for a) and c), and 5V for b) and d). A gate voltage was varied from +2 V to –5 V by 1 V step for (a) and (b), and from +2 V to –2 V by 0.5 V step for (c) and (d). For structure C, current collapse occurred at 50 V operation at positive Vg region as shown in d).

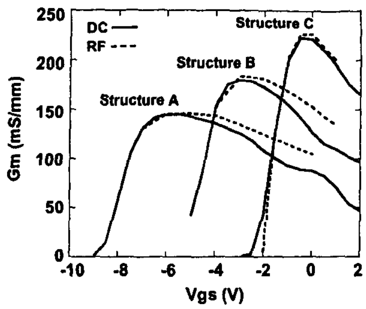


Fig. 6. Transconductance (gm) as a function of Vgs for different structures shown in Table I. Wg=80 μm. Solid lines show DC-gm under DC measurement and dashed lines show RF-gm by S-parameter measurement. RF-gm is defined as an average gm between 1 GHz and 3 GHz.

Linear gain of 9.7 dB with power added efficiency (PAE) of 29% was obtained for structure B. Structure C showed 10% lower PAE due to large current collapse. Pout for structure C was saturated at lower Pin compared structure B.

IV. Conclusion

In summary, we fabricated 24-mm-wide-gate AlGaN/GaN HEMTs using a surface-charge-controlled n-GaN-cap structure on SiC. We concluded that optimum Vth should be considered to obtain high BVgd and to suppress current collapse. We demonstrate high voltage CW operation exhibiting high total output power of 36 W at 30 V. This high voltage operation with high current density was obtained only by optimizing Vth of surface-charge-controlled structure.

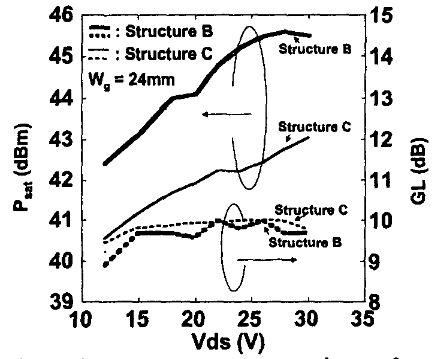


Fig. 7. CW power measurement results as a function of Vds. Measured frequency is 2.2 GHz. Gate width is 24 mm. Packaged chip was measured.

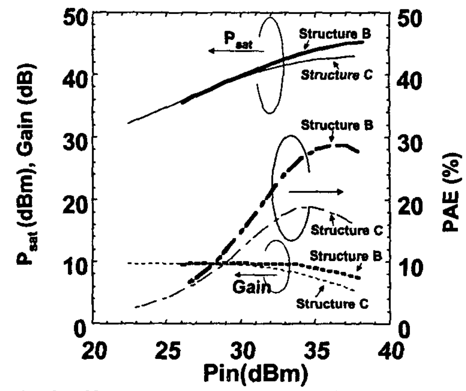


Fig. 8. CW power measurement results at 30 V as a function of Pin. Measured frequency is 2.2 GHz. Gate length is 0.9 μm. Gate width is 24 mm. Packaged chip was measured.

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