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# Improved Electrical Characteristics of AlGaN/GaN HEMT with *In-situ* Deposited Silicon Carbon Nitride Cap Layer

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## 1. Introduction

Passivation of an AlGaN/GaN heterostructure is essential to improve the surface states which can cause the leakage current and current collapse. Generally, passivation layers are grown separately with epi-layers (*ex-situ*). It was also reported that an *in-situ* grown $SiN_x$ layer is more effective in passivating the surface of the AlGaN/GaN HEMT, because epi-layers are protected during processing [1].

Protection diodes were used to protect the device during IC operations, like class-S switch mode amplifier and power switching ICs. There are some researches on AlGaN/GaN HEMT with an integrated Schottky-drain protection diode [2], [3]. The problem of this approach is a reduced drain current due to the voltage drop and resistance of a Schottky-drain diode.

In this study, we demonstrated the AlGaN/GaN HEMT with an *in-situ* deposited silicon carbon nitride (SiCN) cap layer for improved electrical characteristics. Self protected HEMT with a reverse drain blocking capability were also demonstrated on SiCN cap layer.

## 2. AlGaN/GaN HEMT with a SiCN cap layer (SiCN-HEMT)

AlGaN/GaN heterostructure with the *in-situ* SiCN cap layer proposed in this paper was grown on 4-in (0001) *c*-plane sapphire substrates using MOCVD [4]. TMGa, TMAl, $CBr_4$, DTBSi, and $NH_3$ were used for the precursors for Ga, Al, C, Si, and N, respectively. The layer structure consists of a 30-nm-thick low temperature (LT) GaN initial nucleation layer, a 3-µm-thick highly resistive GaN buffer layer, a 25-nm-thick $Al_{0.27}Ga_{0.73}N$ barrier, and a 5-nm-thick SiCN cap layer in growth sequence. All layers except the LT-GaN nucleation layer were grown at 1100 °C. A conventional AlGaN/GaN heterostructure without the SiCN cap layer was grown for comparison.

Root-mean-square roughness of the surface with and without SiCN cap layer was 0.48 and 0.50 nm, respectively. Hall measurement data for AlGaN/GaN heterostructure with and without SiCN cap layer are summarized in table 1. 2DEG carrier concentration was increased about 51 % with SiCN cap layer. Possible reason for the increase of 2DEG concentration is the positive interface ionic charges generated during the growth of the SiCN cap layer, such as $Si^+$ [5]. The Si atoms located at the SiCN/AlGaN interface act as positively charged ionized donors and hence partially neutralize the negative polarization charges of the AlGaN surface, which thereby increases the 2DEG density to satisfy the charge neutrality [4].

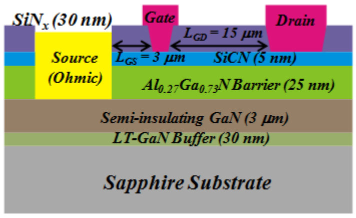


Fig. 1. Schematic sketch of the fabricated SiCN-HEMT

| Sample | Without SiCN | With SiCN 5 nm |
|---|---|---|
| 2DEG mobility µ ($cm^2/V{\cdot}s$) | 1593 | 1270 |
| Carrier concentration $n_s$ ($10^{12}/cm^2$) | 7.79 | 11.77 |
| $\mu \cdot n_s$ ($10^{12}/V \cdot s$) | 12406.8 | 14943.7 |

Table 1. Hall measurement data for samples with and without the SiCN cap layer

Device mesa isolation was performed using $BCl_3/Cl_2$ mixture by inductively coupled plasma reactive ion etching (ICP-RIE). After cleaning with piranha and diluted HF (1:10) for 10 min, 30-nm-thick $SiN_x$ layer was deposited using inductively coupled plasma chemical vapor deposition (ICP-CVD) at 350 °C. Ohmic contact metals of Si/Ti/Al/Mo/Au (5/20/80/35/50 nm) were deposited and followed by thermal annealing at 820 °C for 30 s in $N_2$ ambient. The measured contact resistance and sheet resistance were 0.25 Ω·mm and 368 Ω/sq, respectively. Next, wet etching was used to etch the gate window, because $SF_6$ gas plasma can etch the SiCN cap layer. The next patterning process defined the gate and gate field plates. Finally, Ni/Au (20/380 nm) was deposited as a gate metal.

A schematic sketch of the fabricated GaN HEMT is shown in Fig. 1. The gate length ($L_G$) and gate field plate length were 2 µm. The gate-to-source distance ($L_{GS}$) and gate-to-drain distance ($L_{GD}$) was 3 and 15 µm, respectively. Table 2 and figure 2 show the measured output characteristics of fabricated HEMTs with respect to thickness of the SiCN cap layer. Maximum drain current was increased 15 % in SiCN-HEMT compared with the reference HEMT. Maximum transconductance was also increased 10 %, even though gate-to-channel distance was increased by the SiCN layer thickness. The reason for these improvements in SiCN-HEMT is due to the increase of the carrier concentration. The decrease of gate leakage current in

SiCN-HEMT can be explained by the reduction of a tunneling current as explained in [4].

| | Ohmic-drain | | Schottky-drain | |
|---|---|---|---|---|
| SiCN cap layer | none | 5 nm | none | 5 nm |
| $I_{DS, Max}$ (mA/mm) | 453.0 | 523.2 | 443.2 | 486.2 |
| $G_{m, Max}$ (mS/mm) | 130.2 | 143.8 | 133.3 | 142.5 |
| $I_G$ at $V_{GS}$ = -6 V (μA/mm) | 79.2 | 24.9 | 73.8 | 13.3 |

Table 2. Summary of output characteristics fabricated HEMTs

**3. AlGaN/GaN HEMT with an integrated Schottky-drain protection diode**

Purpose of the HEMT with a protection diode is to suppress a current flow in the HEMT during reverse bias conditions. GaN integrated Schottky-drain protection diode is promising, because GaN SBDs show high switching speed with low on resistance and large forward current. Major problem in integrated Schottky-drain protection diode is the knee voltage due to the voltage drop in Schottky contact at drain.

We fabricated the HEMT with an integrated Schottky-drain protection diode. Measured output values of the AlGaN/GaN HEMT with Schottky-drain protection diode are shown in table 2 and figure 3. Maximum drain current and transconductance of the SiCN-HEMT with a Schottky drain were increased by 10 % and 7 %, respectively. Moreover, gate leakage current is reduced in Schottky-drain HEMT compared with ohmic-drain HEMT. However, Schottky-drain causes the decrease of maximum drain current 7 %, compared with an ohmic-drain HEMT. This is because a Schottky-drain has a higher contact resistance than an ohmic-drain. It is encouraging that the drain current can be increased with a SiCN cap layer, even protection diode was integrated. Turn on voltage of the Schottky-drain diode was 0.7 V for both with and without SiCN cap layer.

The reverse drain current in the on-state ($V_{GS}$ = 0 V) and the threshold state ($V_{GS}$ = -4 V) are shown in Fig. 4. It shows the reverse blocking capability over -100 V for both on and threshold state of the Schottky-drain diode. It was expected that a lower knee voltage due to the lower Schottky barrier height of SiCN-SBDs [4]. However, there was not a noticeable difference in a knee voltage with and without SiCN cap layer, as shown in Fig. 3. Thus, further studies are needed to lower the knee voltage.

**4. Conclusion**

Electrical characteristics of AlGaN/GaN HEMT with *in-situ* deposited SiCN cap layer were improved. The SiCN cap layer effectively increases the 2DEG density of AlGaN/GaN heterostructure. Fabricated HEMT shows the enhanced drain current and transconductance without sacrificing the gate leakage current.

Self-protected HEMT with an integrated Schottky-drain diode was also demonstrated. Drain current and gate leakage current of the HEMTs with a SiCN cap layer are also improved like an ohmic-drain HEMT. The reverse blocking capability was over -100 V.

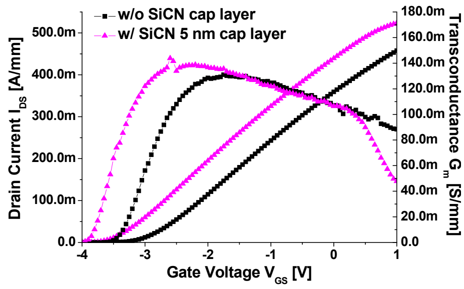


Fig. 2(a). Transfer characteristics and transconductance curve of the fabricated Schottky HEMT ($V_{DS}$ = 10 V)

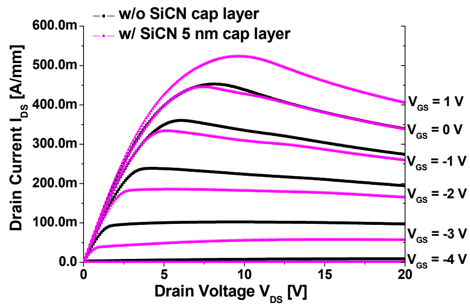


Fig. 2(b). Family curve of fabricated Schottky HEMT

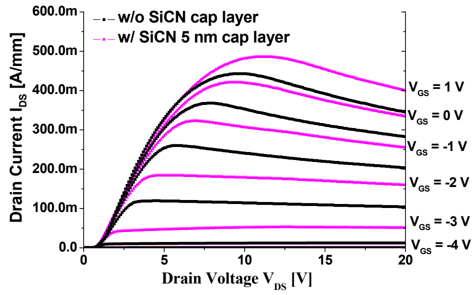


Fig. 3. Family curve of fabricated Schottky-drain HEMT

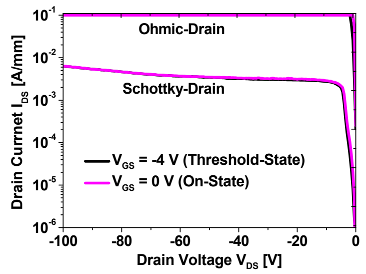


Fig. 4. Reverse blocking capability due to the integrated protection diode

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