The Effects of Gate Metals on the Performance of p-GaN/AlGaN/GaN High Electron Mobility Transistors

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Abstract

The impact of different gate metals- Ni/Au, Ti/Au and Mo/Ti/Au on the performance of p-GaN/AlGaN/GaN high electron mobility transistors (HEMTs) are investigated in this work. Compare to Ni/Au-gate HEMTs, the devices with a Mo/Ti/Au gate can improve 32% of the breakdown voltage with a trade-off of reducing 11% of operating current at L_{GD}=6um. We also demonstrated a noticeably high breakdown voltage of more than 1600V of Ni/Au- and Mo/Ti/Au-gate p-GaN/ AlGaN/GaN HEMTs.

INTRODUCTION

Currently, gallium nitride (GaN) based high electron mobility transistors (HEMTs) have been promising candidates for high-power electronic applications due to their excellent properties, such as high breakdown voltage, high switching frequency, and good thermal stability. Several approaches are applied in order to realize E-mode AlGaN/GaN HEMT devices, for instance, using the p-type cap layer[1], metal-insulator-semiconductor (MIS) structure[2], the fluorine-treatment[3] and so on.

Among the above technologies, p-type GaN HEMTs have the advantage of good controllability of threshold voltage (V_{th}). Although most of literatures on p-type gate GaN HEMTs demonstrated Ni/Au gate metal, there are much more choices of gate metals for p-GaN cap HEMTs than conventional HEMTs since most of the metals have adequate work function difference comparing to p-GaN. Therefore, other metals can be utilized to promote the performance of GaN HEMTs, such as an increase of the V_{th}s or saturated drain currents.

In this work, p-GaN/AlGaN/GaN HEMTs with different gate metals including Ni/Au, Ti/Au and Mo/Ti/Au were studied. The influences of gate metals on the currents, V_{th}s, and breakdown voltages were investigated. We conclude that saturated drain currents involve a trade-off with not only the V_{th}s but also the breakdown voltages. Noticeable high breakdown voltages of 1600V were also demonstrated in Ni/Au- and Mo/Ti/Au-gate HEMTs.

DEVICE FABRICATION

The epi-structure was grown on a Si(111) substrate by metal organic chemical vapor deposition (MOCVD). The layers were composed of a 2.4μm buffer, a 1.2 μm GaN, a 10nm $Al_{0.25}Ga_{0.75}N$ barrier and a 60nm Mg-doped p-type GaN layer. The active p-GaN doping density, intended to deplete the two-dimensional electron gas (2DEG) carriers at the AlGaN/GaN interface, ranges from $1x10^{18}$ to $2x10^{18}$ cm^{-3}. The process was started from defining the mesa area by inductively coupled plasma reactive ion etching (ICP-RIE). Then, the p-GaN layer except the gate contact region was etched by ICP-RIE with Cl_2/BCl_3. For source and drain contacts, Ti/Al/Ni/Au was evaporated by e-gun metal evaporator and alloyed at 900℃ for 30s by rapid thermal annealing (RTA). Afterwards, Ni/Au- and Ti/Au-gate metals were deposited by e-gun metal evaporator for each HEMTs, while Mo was sputtered on a Ti/Au thin film deposited by e-gun metal evaporator. The gate-source (L_{GS}), gate length (L_G), gate–drain offset length (L_{GD}) and gate width is 2, 4, 6 and 50μm, respectively.

RESULTS AND DISCUSSION

We demonstrated three kinds of gate metal in this work, including Ni/Au, Ti/Au and Mo/Ti/Au. Ni/Au is used widely as a metal gate in the commercial GaN HEMTs. We also utilize Ti/Au as a gate metal in order to investigate the potential of processing S/D and gate simultaneously. Considering the effective Schottky barrier height of as low as 0.8eV for Ti/p-GaN contact [4], Mo was sputtered underneath Ti/Au for the other devices.

Transfer curves of the p-GaN cap HEMTs with three kinds of gate metals were measured to investigate the impact of the gate metal on the V_{th}, which was defined by the gate bias at a drain current of 1mA/mm. As shown in Fig. 1, the transfer curve of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs exhibits the V_{th} of 2.19V, 1.78V and 2.39V, respectively.

The I_D-V_{DS} characteristics for Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs are shown in Fig.2 (a), (b) and (c), respectively. The saturated drain current of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs is 194mA/mm, 223mA/mm and 174mA/mm at V_{GS}=10V and V_{DS}=10V, respectively. The largest saturated drain currents of Ti/Au-gate HEMTs can be attributed to the largest value of V_{GS}-V_{th}.

Besides, Ti/Au-gate HEMTs can achieve the smallest on-resistance among the three different gate metal HEMTs. It shows that using Ti/Au as a gate metal can not only decrease the V_{th} but also decrease the on-resistance of a p-GaN AlGaN/GaN HEMT effectively.

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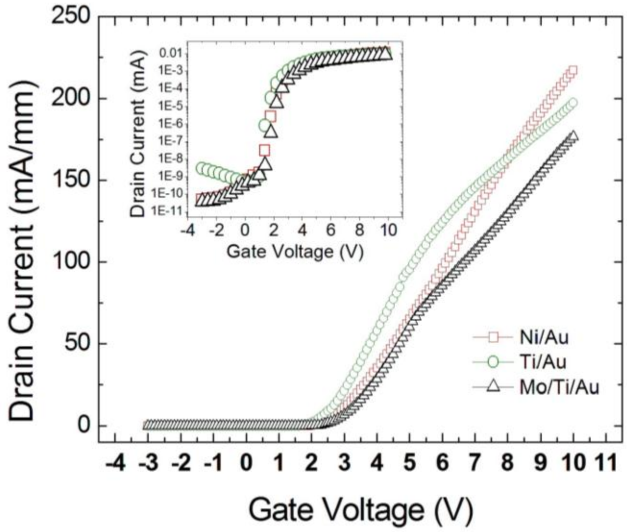

Fig. 1 Transfer characteristics of Ni/Au-, Ti/Au-, and Mo/Ti/Au-gate HEMTs. The drain current is expressed in linear (main plot) and logarithmic (inset) scale.

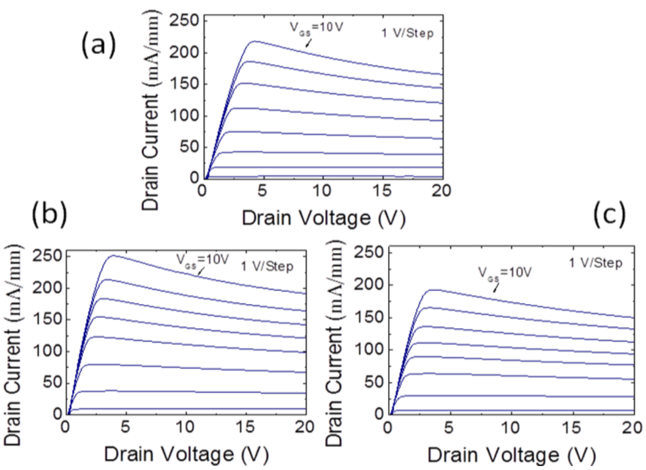

Fig. 2 I_{DS}-V_D curves of HEMTs with (a)Ni/Au , (b)Ti/Au, and (c)Mo/Ti/Au gate metal.

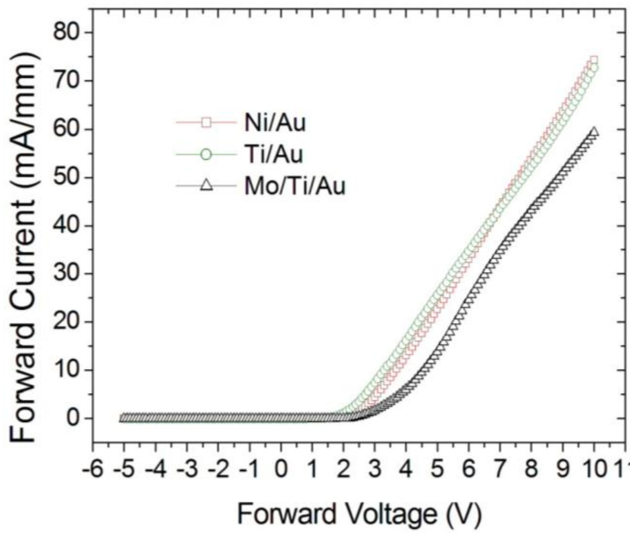

Fig. 3 Forward characteristics of the embedded gate to drain SBD in Ni/Au-, Ti/Au-, and Mo/Ti/Au-gate HEMTs.

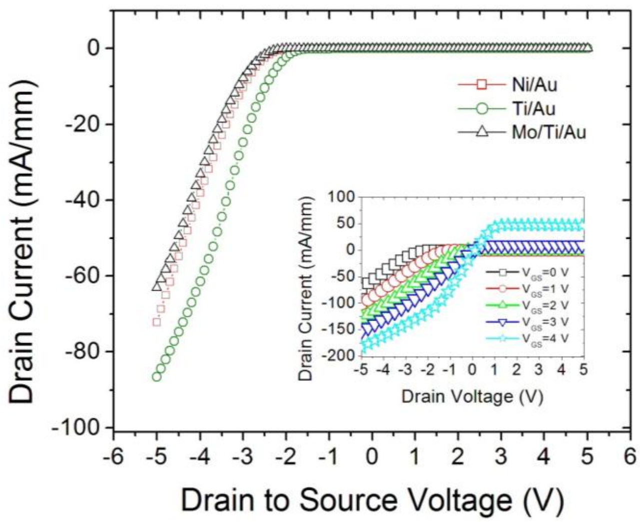

Fig.4 (main plot) The forward characteristic of reverse diode of Ni/Au-, Ti/Au-, and Mo/Ti/Au- gate HEMTs when V_{GS}=0V. (inset) On-state I_D-V_{DS} curves of both forward and reverse operations for Ni/Au-gate HEMT.

Since the energy level of the valence band edge of GaN is deeper than the work functions of the three used metals, the contact between metals and p-GaN shows Schottky-type characteristics. Work function difference between p-GaN and metals, Ni, Ti and Mo, is 2.35 eV, 3.17 eV and 2.9 eV, respectively. Thus, V_{th} of HEMTs do not correspond to a theoretical Schottky barrier height of gate metal/p-GaN contact directly. Instead, they are influenced by a real barrier height of Ni/, Ti/, and Mo/p-GaN contact.

Compared with Ni/Au- and Mo/Ti/Au-gate HEMTs, the V_{th} of Mo/Ti/Au-gate HEMTs is 0.2V higher than this of Ni/Au-gate HEMTs. This result implies that p- GaN HEMTs with a higher real Schottky barrier height of the metal/p-GaN contact have a higher V_{th}. On the other hand, the V_{th} of Ti/Au-gate HEMTs is much lower than the other devices due to the smallest effective Schottky barrier height of only 0.8eV of Ti/p-GaN. As shown in the inset of Fig.1, the on/off current ratio of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs is of 2.26×10^8, 3.32×10^6, and 2.33×10^8, respectively. The weaker ability of Ti/Au-gate HEMTs to restrain leakage current can be contributed to the low real Schottky barrier height.

The gate to drain region can be regarded as a Schottky barrier diode (SBD) embedded in the HEMT structure. V_{th} can be considered as the approximate turn-on voltage of a p-n diode composed of p-GaN/2DEG. When the p-n diode is on, the depletion region width in 2DEG side reduces and a channel is created. As a result, it implies that the turn-on voltage of SBDs is closely associated with Schottky barrier height of HEMTs.

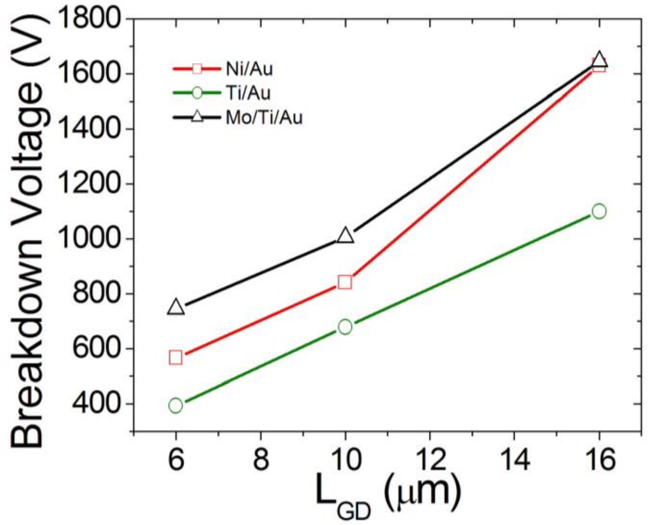

Fig. 5 Breakdown voltage of Ni/Au-, Ti/Au-, and Mo/Ti/Au-gate HEMTs with various L_{GD}.

To further investigate the relationship between the V_{th} and real Schottky barrier height of different gate metal HEMTs, the forward characteristics of the embedded SBD in Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs are measured and shown in the Fig.3. The corresponding turn-on voltages defined at 1mA/mm are 2.35V, 1.97V and 2.77V for the SBDs embedded in Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs, respectively. The highest turn-on voltage of the SBD embedded in Mo/Ti/Au-gate HEMT can be attributed to the highest Schottky barrier height of Mo/p-GaN contact. It indicates that HEMTs cannot achieve a high V_{th} only by having a gate metal with a low work function; alternatively, the high effective barrier height of metal/p-GaN is crucial.

Also, the SBD embedded in Mo/Ti/Au-gate HEMT has 15mA/mm lower current than the forward current of other diodes at forward voltage is 10V. The result reveals a trade-off between the turn-on voltage and the forward current, and corresponds to the relationship between the V_{th} and output current.

For conventional half bridge inverter, the low-side transistor needs to be driven to flow the fly-wheel current in order to prevent an overvoltage induced by the inductor. As shown in Fig.4, the p-GaN cap HEMTs behave as a diode when operated at reverse conduction mode. When V_{GS}= 0V, the reverse current supplied by an inductive load is allowed to flow through the HEMTs from source to drain. Since the diodes are embedded in the HEMT structure, the turn-on voltage of diode is similar to the V_{th} of the corresponding HEMT. The turn-on voltage defined at 1mA/mm of each reverse diode in the Ni/Au- , Ti/Au, and Mo/Ti/Au-gate HEMTs is -2.26V, -1.83V, and -2.4V, respectively. The current conducted by reverse diode of Ti/Au-gate HEMT is the largest while it of Mo/Ti/Au-gate HEMT is the smallest.

The breakdown characteristics for Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs were also measured, which are shown in Fig. 3. No matter which gate metal is used, the breakdown voltages of HEMTs increased with the length of L_{GD}. While L_{GD} is 6μm and 10μm, the breakdown voltages of Mo/Ti/Au-gate HEMTs are largest, and this of Ti/Au-gate HEMTs are smallest. It is because that higher barrier height between Mo and p-GaN can effectively restrain the leakage currents when HEMTs are in the off-state. Generally, similar order of off-state current can be obtained from Mo/Ti/Au- and Ni/Au-gate HEMTs, but larger off-state current orders of Ti/Au-gate HEMTs are typically measured, which result in a lower breakdown voltage of Ti/Au-gate HEMTs. When L_{GD} is 16um, the breakdown mechanism is related to buffer leakage, so the breakdown voltages of Ni/Au- is similar to this of Mo/Ti/Au-gate HEMTs. Breakdown voltages of as high as 1600V were demonstrated with the design of 2.4 um buffer and 1.2um GaN.

CONCLUSIONS

P-GaN cap HEMTs with different gate metals were demonstrated in this report. We conclude that gate metal/p-GaN contacts have an impact on the performance of the E-mode HEMTs, such as the V_{th}s, output drain currents, breakdown voltages and so on. Compare to Ni/Au-gate HEMTs, the devices with a Mo/Ti/Au gate can improve 32% of the breakdown voltage with a trade-off of reducing 11% of operating current at L_{GD}=6um. Moreover, both Ni/Au- and Mo/Ti/Au-gate HEMTs exist noticeably high breakdown voltage up to 1600V when L_{GD} is 16μm.

REFERENCES

[1] O. Hilt, A. *et al.*, "Normally-off AlGaN/GaN HFET with p-type GaN Gate and AlGaN buffer," in Int. Sym. Pow. Semicond., June 2010, pp. 347-350.

[2] Y. Chang, *et al.*, "Inversion-channel GaN MOSFET using atomic-layer-deposited Al 2 O 3 as gate dielectric," Appl. Phys. Lett., vol. 93, pp. 053504-053504-3, Aug. 2008.

[3] Y. CAI, *et al.*,"HIGH-PERFORMANCE ENHANCEMENT-MODE ALGAN/GAN HEMTS USING FLUORIDE-BASED PLASMA TREATMENT," IEEE ELECTRON DEVIC. LETT., VOL. 26, PP. 435-437, JUL. 2005.

[4] Z. Z. BANDIC, *et al.*,"ELECTRON DIFFUSION LENGTH AND LIFETIME IN P-TYPE GAN," Appl. Phys. Lett., vol. 77, pp. 3276-3278, Nov. 1998.

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