Impact of Gate Metal on the Performance of p-GaN/AlGaN/GaN High Electron Mobility Transistors

Finella Lee, Liang-Yu Su, Chih-Hao Wang, Yuh-Renn Wu, and Jianjang Huang, *Senior Member, IEEE*

***Abstract*— For conventional GaN-based high electron mobility transistors (HEMTs), the work function of gate metal is critical to electrical parameters, such as OFF-state leakage current, forward operating current, and threshold voltage. A high work function is thus required to maintain Schottky gate contact. In this letter, an enhancement-mode HEMT composed of p-type GaN/AlGaN/GaN was fabricated. Unlike typical HEMTs that the Schottky barrier height is determined by the energy difference between gate metal work function and semiconductor (AlGaN, or GaN) conduction band, the insertion of the p-GaN relieves the constraint of gate metal. In addition, the gate Schottky barrier now correlates to the valence band of the semiconductor. Here we compare the HEMT performance of different gate metals—Ni/Au, Ti/Au, and Mo/Ti/Au. The results reveal that a tradeoff between V_{TH} and output drain current.**

***Index Terms*— HEMT, enhancement mode, threshold voltage.**

I. Introduction

In recent years, gallium nitride (GaN) based high electron mobility transistors (HEMTs) have attracted considerable attention in high-power electronics because of their superior properties, such as high-breakdown voltage, high-switching frequency, and good-thermal stability. For conventional AlGaN/GaN HEMT structures, two dimensional electron gas (2DEG) inherently exists in the interface of GaN due to the strong built-in polarization electric field in the AlGaN/GaN heterostructure. The 2DEG cannot be easily depleted by the Schottky gate contact at zero bias. Such a depletion-mode (D-mode) behavior excludes GaN based transistors from most power electronic applications. In order to achieve enhanced-mode (E-mode) HEMTs, several technologies have been developed to raise the conduction band energy level (E_C) underneath the gate contact to obtain a positive threshold voltage (V_{TH}). For instance, p-type cap layer [1]–[3], metal insulator semiconductor (MIS) structure [4], fluorine-treatment [5] have been proposed to deplete the 2DEG carriers in the AlGaN/GaN interface, thus lifting up E_C underneath the gate contact. Our previous work [1] compared device performance under different structures and process conditions of the p-GaN/AlGaN/GaN HEMTs. The results show that a threshold voltage ranging from 1.6 to 4.3V with a heavily doped p-GaN cap layer. The gate voltage is operated up to 10V [1]. For the E-mode p-GaN/AlGaN/GaN HEMT structure in Fig. 1(a), by employing the Poisson equation [6], we can obtain the energy band profiles at the gate bias of 0V for a Ni gate contact case. As in Fig. 1(b), the 2DEG carriers are depleted as the Fermi level is below the GaN conduction band. On the other hand, to reach the flat band condition at the GaN layer, a positive gate voltage has to be applied by considering the schottky barrier at the gate metal/p-GaN and the voltage across the AlGaN layer. As the gate voltage is above V_{TH}, 2DEG carriers start to accumulate in the channel. The band diagrams at gate voltage (V_{GS}) of 3V are shown in Fig. 1(c) based from a simulation using the drift-diffusion charge control model [6].

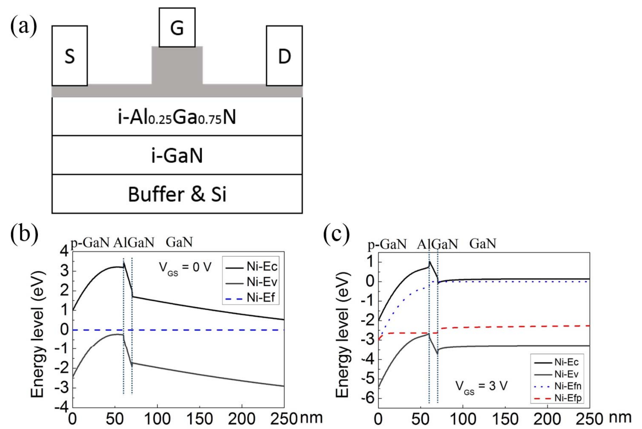

Fig. 1. (a) Schematic of the E-mode p-GaN/AlGaN/GaN HEMT. (b) Band diagram of the E-mode p-GaN/AlGaN/GaN structure at $V_{GS} = 0$. The conduction band of GaN is above the Fermi level, indicating a delpeted 2-DEG channel. (c) At $V_{GS} = 3$ V. Both (b) and (c) are in the case that uses Ni as the gate metal.

For conventional GaN HEMTs, either E- or D-mode devices, 2DEG carriers in the channel are modulated by the Schottky gate. The Schottky barrier height between gate contact metal and semiconductor determines the electrical characteristics including current collapse, leakage current, *et al.* In the AlGaN/GaN structure, the barrier height is usually proportional to the energy difference between the gate metal work function and E_C. Moreover, such a HEMT device has a large gate leakage current, which limits the maximum gate voltage swing [7]. The choices of

Manuscript received January 5, 2015; accepted January 14, 2015. Date of publication January 22, 2015; date of current version February 20, 2015. This work was supported by the Bureau of Energy, Taiwan's Ministry of Economics Affairs, through National Taiwan University, Taipei, Taiwan, under Grant 102-E0610. The review of this letter was arranged by Editor T. Egawa.

F. Lee, L.-Y. Su, C.-H. Wang, and Y.-R. Wu are with the Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 10617, Taiwan.

J. Huang is with the Department of Electrical Engineering, Institute of Photonics and Optoelectronics, National Taiwan University, Taipei 10617, Taiwan (e-mail: jjhuang@ntu.edu.tw).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LED.2015.2395454

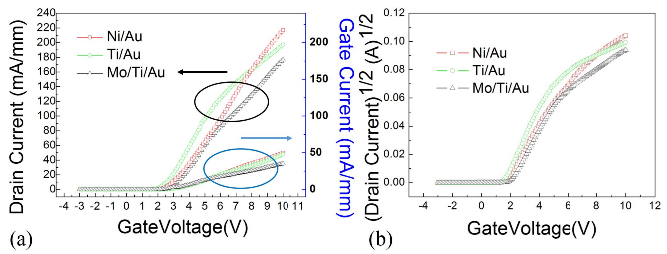

Fig. 2. (a) Transfer characteristics of the devices at $V_{DS} = 5$ V. The gate currents of three devices are also plotted. (b) $(I_D)^{1/2}$ v.s. V_{GS} curves for extrapolating V_{TH}.

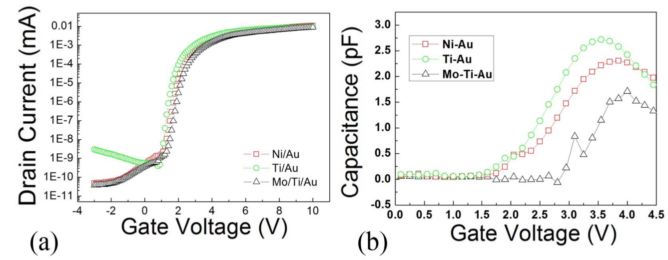

Fig. 3. (a) Transfer characteristics of Ni/Au-, Ti/Au-, and Mo/Ti/Au-gate HEMTs. The drain current is expressed in logarithmic scale. (b) C-V curves of Ni/Au-, Ti/Au-, and Mo/Ti/Au-gate HEMTs.

gate metal are limited because a sufficient barrier height is required to maintain device operations including gate leakage, and gate voltage control carrier/current level.

For the E-mode structure in Fig. 1(a), the insertion of a p-GaN layer underneath the gate metal results in the re-adjustment of Schottky barrier height, which is correlated to energy difference of metal work function and valence band of p-type GaN (E_V), instead of E_C. Previous idea of selecting high work function metal for Schottky gate contact may not be a necessary condition. In this letter, we deposited different gate metal stacks including Ni/Au, Ti/Au and Mo/Ti/Au on p-GaN/AlGaN/GaN E-mode HEMTs. We studied the impact of p-GaN barrier height on the device performance. The corresponding electrical properties, such as V_{TH}, saturation output current, and gate leakage of GaN HEMTs were studied.

II. Device Fabrication

Our epi-structure was grown on a Si(111) substrate by metal organic chemical vapor deposition (MOCVD), which is composed of a 2.4μm-thick buffer, a 1.2μm 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, is in the range of 1×10^{18} to 2×10^{18} cm^{-3}.

Device fabrication started from defining the mesa area by inductively coupled plasma reactive ion etching (ICP-RIE). The p-GaN gate island was then formed by ICP-RIE with the etching gas Cl_2/BCl_3. For source and drain contacts, Ti/Al/Ni/Au was evaporated by e-beam evaporator and alloyed at 900 °C for 30s by rapid thermal annealing (RTA). Next, we evaporated gate metal. Here we studied three types of devices, which Ni/Au-, Ti/Au- and Mo/Ti/Au-gate electrodes were employed, respectively. All the above metal stacks were deposited by evaporation except the DC sputter was used for Mo. 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.

III. Results and Discussion

The current-voltage transfer curves at V_{DS} (drain-source voltage) of 5V were first investigated and shown in Fig. 2(a). V_{TH} was obtained from extrapolating the square root of drain current ($(I_D)^{1/2}$) in Fig. 2(b). For Ni/Au-, Ti/Au- and Mo/Ti/Au-gate electrode, V_{TH} is 1.8, 1.7 and 1.9, respectively. Since the valence band energy level (E_V) of GaN is deeper than the work function of selected gate metal in our study, gate contact on the p-GaN still shows Schottky-type characteristics. Theoretical E_V/work function difference between p-GaN and Ni, Ti and Mo, is 2.4, 3.2 and 2.9 eV, respectively [8]. Literature indicates that V_{TH} of HEMTs increases with the Schottky barrier height [9]. In our devices, V_{TH} of the Mo/Ti/Au-gate HEMT is 0.2V higher than that of the Ni/Au-device, which the trend follows expectation because the Schottky barrier height of the Mo/Ti/Au-gate HEMT is 0.5eV higher than that of the Ni/Au-gate device. Furthermore, the gate currents of three devices are shown in Fig. 2(a). With the increase of gate bias, hole injection from p-GaN increases channel conductivity [2]. At a high gate bias of 10V, Mo/Ti/Au-gate HEMT possesses the lowest gate current, which is correlated to a higher work function/E_V difference.

However, the lowest V_{TH} of the Ti/Au-gate HEMT among the devices can't be explained based on the theoretical work function and E_V difference between p-GaN and Ti. Literature on the barrier height between Ti and p-GaN is only 0.9 eV, much lower than the theoretical barrier height [10]. This phenomenon is partially due to holes tunneling through the very thin barrier formed at the Ti/p-GaN contact because high Mg acceptor concentration causes image-force lowering effect. Also, electrons diffusion through the Schottky contact are to induce currents [10].

The extracted Schottky barrier height between Ti/p-GaN interface agrees with the literature report. As in Fig. 3 (a), the drain current of Ti/Au-gate HEMTs is about two orders of magnitude higher than other devices at $V_{GS} = -5$V. The large leakage current of the Ti/Au-gate HEMT is attributed to the low effective Schottky barrier height in the Ti/p-GaN interface when these three devices are compared. In addition, as shown in Fig. 3 (a), the on/off current ratio of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs is 2.26×10^8, 3.32×10^6, and 2.33×10^8, respectively. Again the smaller on/off current ratio of Ti/Au-gate HEMT is due to the larger leakage current.

The V_{TH} difference between devices is further verified by capacitance measurement. In Fig. 3(b), V_{TH} measured from gate-source C-V (capacitance-voltage) curves of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs is 1.7, 1.6 and 2.6 V, respectively. The results follow the trend of transfer curve in Fig. 2.

To further investigate the relationship between V_{TH} and real Schottky barrier height of different gate metals, the forward characteristics of the embedded SBD in gate to drain contact

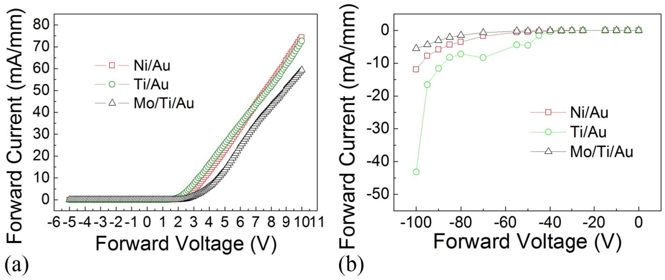

Fig. 4. (a) Forward characteristics of the embedded gate-to-drain SBD in HEMT structure. (b) The leakage current of the embedded gate-to-drain SBD up to a reverse voltage (forward voltage in the negative value) of 100V.

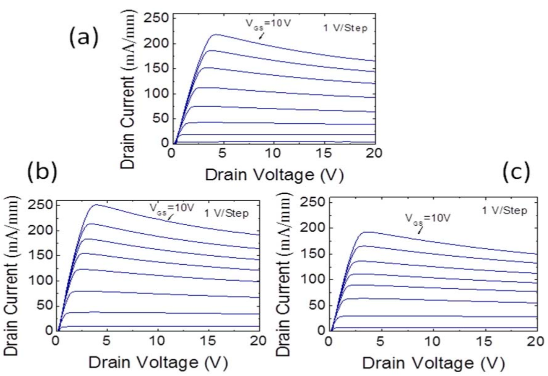

Fig. 5. I_D–V_{DS} characteristics for (a) Ni/Au, (b) Ti/Au, and (c) Mo/Ti/Au-gate HEMTs.

structure were studied. As in Fig. 4(a), the corresponding turn-on voltages defined at 1mA/mm are 2.4V, 2.0V and 2.8V for the SBDs embedded in Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs, respectively. The reverse leakage currents of three embedded devices at a voltage up to −100V are shown in Fig. 4(b). Mo/Ti/Au gate has the lowest leakage current while the Ti/Au has the highest one.

In Fig. 1, the band diagrams show that the p-GaN layer is composed of two regions. Holes that are close to the surface are depleted, while holes in p-GaN close to the p-GaN/AlGaN interface tend to be accumulated when positive bias is applied (meaning holes are pushed to the GaN/AlGaN interface). When the gate bias is larger than the V_{TH}, electrons and holes accumulate at either side and the capacitance reaches a maximum that is decided by the AlGaN layer (see Fig.1 (c)). When the bias continues to increase, the gate leakage occurs and the equivalent capacitance drops again. Since Ti gate metal has the lowest energy barrier (relative to valence band), the depletion is weaker and holes are much easier to be injected into the p-GaN layer and accumulated at the GaN/AlGaN interface. The injection of holes pulls down the potential, leading to a faster electron accumulation and a smaller Vth. For the Mo case with larger E_V/work function difference, the depletion field is larger but holes are much harder to be injected into the p-GaN layer. Therefore, the accumulation of holes at GaN/AlGaN interface is less and potential at p-GaN/AlGaN interface is relative higher compared to the Ti case.

The I_D–V_{DS} characteristics of the HEMT structure are shown in Fig. 5(a), (b) and (c), respectively. The saturated drain current of Ni/Au-, Ti/Au- and Mo/Ti/Au-gate HEMTs is 194, 223 and 174mA/mm at $V_{GS} = 10V$ and $V_{DS} = 10V$, respectively. The largest saturated drain current of Ti/Au-gate HEMTs is mainly attributed to the lowest Schottky barrier height between Ti/p-GaN. In addition, Ti/Au-gate HEMTs have the largest (V_{GS}−V_{TH}) value. To pursue E-mode HEMTs with a positive threshold voltage and a high drain current level, our discussion above reveals a trade-off between V_{TH} and output current in the device with p-GaN/AlGaN/GaN structure.

IV. Conclusion

Electrical performances of E-mode HEMTs with different gate metals were demonstrated. The gate Schottky barrier is correlated to semiconductor (GaN or AlGaN) valence band (instead of conduction band in typical GaN HEMT structure). For the gate metal with a low effective work function, a higher V_{TH} can be achieved because the depletion region width across metal/p-GaN junction increases. Moreover, gate current through the Schottky barrier is much larger for the gate electrode with a higher gate work function. Our discussion above reveals a trade-off between V_{TH} and output current in the device with p-GaN/AlGaN/GaN structure.

References

[1] L.-Y. Su, F. Lee, and J. J. Huang, "Enhancement-mode GaN-based high-electron mobility transistors on the Si substrate with a P-Type GaN cap layer," *IEEE Trans. Electron Devices*, vol. 61, no. 2, pp. 460–465, Feb. 2014.

[2] Y. Uemoto *et al.*, "Gate injection transistor (GIT)—A normally-off AlGaN/GaN power transistor using conductivity modulation," *IEEE Trans. Electron Devices*, vol. 54, no. 12, pp. 3393–3399, Dec. 2007.

[3] I. Hwang *et al.*, "p-GaN gate HEMTs with tungsten gate metal for high threshold voltage and low gate current," *IEEE Electron Device Lett.*, vol. 34, no. 2, pp. 202–204, Feb. 2013.

[4] Y. C. Chang *et al.*, "Inversion-channel GaN metal-oxide-semiconductor field-effect transistor with atomic-layer-deposited Al_2O_3 as gate dielectric," *Appl. Phys. Lett.*, vol. 93, no. 5, pp. 053504-1–053504-3, Aug. 2008.

[5] Y. Cai *et al.*, "High-performance enhancement-mode AlGaN/GaN HEMTs using fluoride-based plasma treatment," *IEEE Electron Device Lett.*, vol. 26, no. 7, pp. 435–437, Jul. 2005.

[6] Y.-R. Wu, M. Singh, and J. Singh, "Gate leakage suppression and contact engineering in nitride heterostructures," *J. Appl. Phys.*, vol. 94, no. 9, pp. 5826–5831, 2003.

[7] T. Hashizume *et al.*, "Al_2O_3 insulated-gate structure for AlGaN/GaN heterostructure field effect transistors having thin AlGaN barrier layers," *Jpn. J. Appl. Phys.*, vol. 43, no. 6B, pp. L777–L779, Jun. 2004.

[8] S. Hałas, "100 years of work function," *Mater. Sci.-Poland*, vol. 24, no. 4, p. 952, 2006.

[9] T. Kimura *et al.*, "Shift in threshold voltage and Schottky barrier height of molybdenum gate gallium arsenide field effect transistors after high forward gate current test," *Jpn. J. Appl. Phys.*, vol. 35, no. 7B, pp. L883–L886, Jul. 1996.

[10] Z. Z. Bandic *et al.*, "Electron diffusion length and lifetime in p-type GaN," *Appl. Phys. Lett.*, vol. 73, no. 22, pp. 3276–3278, Nov. 1998.