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Gate conduction mechanisms and high V_{th} stability of Cu-gated p-GaN HEMT

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P-GaN HEMTs with low gate leakage and stable V_{th} are crucially important for the design and application of GaN-based integrated circuits [1]. The choice of gate metal influences the performance of p-GaN HEMTs, which are usually classified as ohmic-type contacts and Schottky-type contacts. An Ohmic gate leads to hole injection at a high positive gate bias, resulting in a low gate breakdown voltage. The low-leakage Schottky metal/p-GaN junction often brings a notable shift in V_{th}, while the high-leakage Schottky junction leads to a short lifetime of p-GaN HEMTs. Hence the trade-off of gate metal/p-GaN with low leakage and stable performance is essential for high-reliability p-GaN HEMTs. As one of the best conductors with low resistivity, copper is currently being developed for multistage fast and fine interconnects in silicon VLSI technology due to its low electron mobility and low-stress mobility. In this study, Cu-gated p-GaN HEMTs are proposed, and the direct current (DC) characteristics and mechanism of excellent instability in DC/pulse stress are investigated.

Experiment. In this study, p-GaN HEMTs with Ni, Cu, and W gate metals were manufactured, and the device structures are shown in Figures 1(a) and (b). Details of the growth epitaxy and device fabrication process can be found in Appendix A.

Results and discussion. Figures 1(c) and (d) show the transfer characteristics of the p-GaN gate HEMTs with Ni and Cu gate metals in the operating state and the corresponding gate leakage characteristics. All DUTs have a high on/off ratio of 10^8 at room temperature. The Ni/p-GaN gate HEMTs have a V_{th} of 0.6 V. However, an apparent gate injection is present in the Ni/p-GaN HEMTs due to the low barrier height of the Ni/p-GaN interface, which leads to a drop in output current and deteriorates gate reliability, as shown in Figure 1(c). Owing to the high barrier height at the metal-semiconductor interface, the V_{th} of the Cu/p-GaN HEMTs is 0.83 V. Cu/p-GaN HEMTs avoid large gate injection and operate with a low gate leakage current of the order of 10^{-2} mA/mm (@$V_G = 7$ V), combining good output characteristics with safe gate operation. Figure 1(e) shows the gate leakage current of Cu/p-GaN HEMT is almost 5 orders of magnitude lower compared to Ni/p-GaN HEMT. The positive temperature coefficient of breakdown voltage for Cu/p-GaN HEMTs is 0.010 V/°C, as shown in Figure 1(f).

Figure 1(g) illustrates the gate leakage characteristics of Cu/p-GaN HEMT at temperatures from 25°C to 175°C. Strong temperature-dispersion at gate voltages of 0 to 5 V indicates a thermal emission (TE) process [2], which is consistent with the following equation: $J_{\mathrm{TE}} = J_{\mathrm{TE0}}\{\exp\frac{q(V-J_{\mathrm{TE}}R_S)}{nkT}-1\}$ and $J_{\mathrm{TE0}} = A^*T^2\exp(-\frac{q\varphi_{\mathrm{b}}}{kT})$, where $A^* = 27.9\ \mathrm{A\cdot cm^{-2}\cdot K^{-2}}$ is Richardson's constant and $q\varphi_{\mathrm{b}}$ is the effective barrier height, found to be 0.72 eV when extracted from the linear fit of $\ln(J_{\mathrm{TE}}/T^2)$ versus $(kT/q)^{-1}$. For W/p-GaN HEMT, the $q\varphi_{\mathrm{b}}$ is extracted to be 0.87 eV shown in Figure 1(k). The values of these barrier heights deviate from the theoretical value of the Schottky barrier $q\varphi_{\mathrm{schb}}$, which is generally attributed to the Fermi pinning effect at the metal/p-GaN interface [3]. When gate voltage increases from 5 to 7.6 V, trap-assistant tunneling (TAT) dominates the gate conduction, which is given by $J_{\mathrm{TAT}} \propto \exp(\frac{-8\pi\sqrt{2qm_p^*}}{3hE}\varphi_{\mathrm{t}}^{3/2})$, where φ_{t} is the trap energy level, m_p^* is the effective carrier tunneling mass, and h is the Planck constant. The straight line in Figure 1(h) confirms that the main mechanism of Cu/p-GaN HEMT in the medium voltage range ($5\ \mathrm{V} < V_G < 7.6\ \mathrm{V}$) is TAT. In addition, the trap depth $q\varphi_{\mathrm{t}}$ of 0.66 eV can be extracted. For W/p-GaN HEMT, the $q\varphi_{\mathrm{t}}$ is extracted to be 0.85 eV shown in Figure 1(l), which might be the reason for preventing hole injection.

Poole-Frenkel (PF) emission is the dominant trap-assisted leakage process at room temperature and above room temperature under moderate electric fields, as shown in the following equation [4]: $\ln(\frac{I_{\mathrm{PF}}}{E}) = \alpha + \beta_S\cdot\frac{qE^{\frac{1}{2}}}{kT}$, where k is the Boltzmann constant, φ_{PF} is the energy level of the trap state (Figure 1(i)). The consistency of the fitted curves

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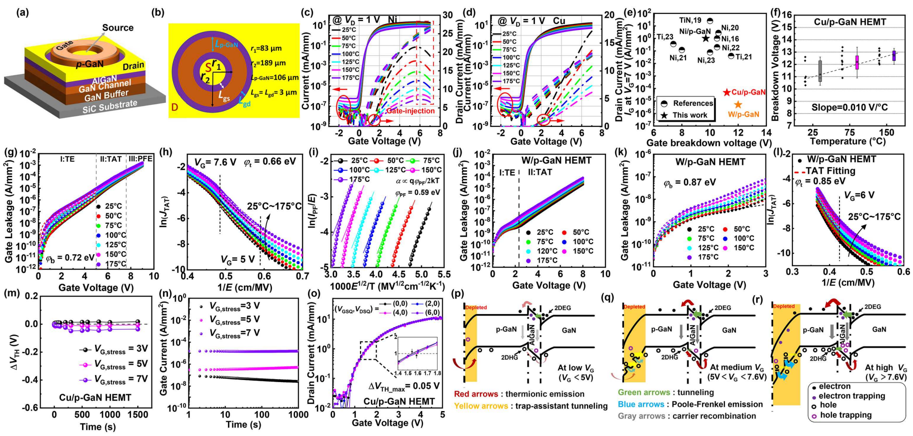

Figure 1 (Color online) (a) Schematic diagram and (b) top view of p-GaN HEMT; transfer and gate leakage characteristics under variable temperatures for (c) Ni/p-GaN HEMTs and (d) Cu/p-GaN HEMTs; (e) comparison between this work and recent studies in terms of gate leakage and gate breakdown voltage; (f) gate breakdown voltage and (g) gate leakage of Cu/p-GaN HEMTs at various temperatures; (h) $\ln(J_{\rm TAT})$ vs. $1/E$ plot and (i) PF plots of Cu/p-GaN HEMT at various temperatures; (j) gate leakage characteristics of W/p-GaN HEMT; (k) I_G of W/p-GaN HEMT at low V_G; (l) $\ln(J_{\rm TAT})$ vs. $1/E$ of W/p-GaN HEMT; (m) threshold drift characteristics and (n) gate leakage in the gate stress test; (o) dynamic double-pulse transfer curves after gate stress; Schematic energy band and carrier transport mechanism diagram of the Cu/p-GaN gate HEMTs at (p) low, (q) medium, and (r) high gate bias.

in Figure 1(i) indicates that the gate leakage mechanism of Cu/p-GaN HEMT is PF emission, which in turn extracts a trap depth ($q\varphi_{\rm PF}$) of 0.59 eV.

For medium-leakage Schottky gate Cu/p-GaN HEMTs, the $V_{\rm th}$ exhibits a small increase at 3 V gate stress and saturates within a very short stress time, with a threshold shift of 0.017 V at a stress duration of 1500 s, as shown in Figure 1(m). Meanwhile, the I_G decreases from 8.85×10^{-8} to 2.72×10^{-8} A/mm^2. At 5 V gate stress, the $V_{\rm th}$ shifts -0.005 V for a stress duration of 1500 s. The I_G increases from 2.98×10^{-7} to 4.97×10^{-7} A/mm^2, and the increased gate leakage indicates that the electrons trapped in the barrier layer are gradually released by the injected holes. At 7 V gate stress, the $V_{\rm th}$ shifts negatively, with a shift of -0.035 V for a duration of 1500 s. The I_G rises from 1.54×10^{-5} to 1.65×10^{-5} A/mm^2. Figure 1(o) shows the pulsed transfer characteristics in the pulsed test with a frequency of 1 MHz and an effective gate stress of 0.5 µs. The maximum threshold shift of Cu/p-GaN HEMT is 0.05 V, due to its more suitable hole injection dose.

Figures 1(p)–(r) demonstrate the carrier transport mechanism of the Cu/p-GaN HEMT under gate stress at low gate voltage (0 V $< V_G <$ 5 V). As the device turns on, some electrons pass through the AlGaN layer to reach the p-GaN, and a portion of them are trapped in the AlGaN layer. A small number of holes overcome the higher effective barrier to reach the valence band of p-GaN or the conductive defect energy level (thermionic emission process) [5], a part of the holes and electrons undergo recombination, a part of them are plunged into the p-GaN/AlGaN interface, the other part enters the interior of the AlGaN to liberate the trapped electrons, and a few holes enter the GaN channel layer. At medium gate voltage (5 V $< V_G <$ 7.6 V), when energy band down bending occurs due to the intensification of the electric field in the depletion region on the p-GaN surface, which allows the holes to enter the p-GaN valence band in the form of trap-assistant tunneling, this process injects more holes than the thermal emission process, which enables more trapped electrons to be liberated, and forward threshold shift to be mitigated. At a high voltage range (7.6 V $< V_G <$ 9 V), the Poole-Frenkel emission dominates the movement of holes. More holes are recombined with electrons in p-GaN, and the holes trapped in the AlGaN layer cause the negative $V_{\rm th}$ shift of the device. The injection of holes in the operating voltage range is crucial for its stability, which affects the transfer characteristics, threshold shift, and lifetime.

Conclusion. This study analyzes the performance and stability of Cu/p-GaN gate HEMTs under gate stress, highlighting the impact of barrier height differences on threshold voltage stability. Cu-gated p-GaN HEMTs exhibit a stable threshold voltage under DC and pulsed stress, and a high gate breakdown voltage of 11.2 V. The integration of Cu-based metallization schemes in p-GaN HEMT provides critical insights into enhancing reliability and paves the way for CMOS-compatible heterogeneous integration.

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Supporting information Appendix A. The supporting information is available online at **info.scichina.com** and **link.springer.com**. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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