Improved Temperature-Dependent Characteristics of a Sulfur-Passivated AlGaAs/InGaAs/GaAs Pseudomorphic High-Electron-Mobility Transistor

Po-Hsien Lai, Ssu-I Fu, Yan-Ying Tsai, Ching-Wen Hung, Chih-Hung Yen, Hung-Ming Chuang, and Wen-Chau Liu

Institute of Microelectronics, Department of Electrical Engineering, National Cheng-Kung University, Tainan, 70101, Taiwan

The temperature-dependent characteristics of (NH₄)₂Sₓ-passivated AlGaAs/InGaAs/GaAs pseudomorphic high electron mobility transistors were studied and demonstrated. Due to the use of sulfur passivation, remarkable improvements in device performance, including higher forward turn-on voltage, higher reverse breakdown voltage, lower reverse leakage current, higher transconductance, lower on-resistance, more linear operating regime, and superior microwave performance, were obtained. In addition, the sulfur-passivated devices also show good properties in the higher operating temperature regime and relatively thermally stable performance over the operation temperature range 300–510 K. Therefore, the studied device with (NH₄)₂Sₓ treatment provides promise for high-performance digital and microwave device applications.

Due to progressive improvements in growth techniques, heterostructure field-effect transistors (HFETs) have been studied extensively for high-speed microwave applications. Nevertheless, the III-V HFETs may suffer from surface-related mechanisms. The surface of III-V semiconductor materials such as AlGaAs is known to be plagued by a high density of interface states. Furthermore, the extrinsic surface, formed by the typical gate-recess etching processes, traps a significant portion of the electrons and causes the increase of the depletion layer between the source and the gate edge near the source. This adversely influences the effect of applied gate bias on the active channel and results in reduced transconductance and poor long-term device stability. Therefore, the lack of an adequate surface passivation for the III-V HFETs severely degrades device performance and restricts application of compound semiconductor devices. In order to overcome this undesirable problem, the surface passivation becomes a crucial requirement for fabricating high-performance electronic and optoelectronic devices. In particular, sulfur passivation in a wet chemical solution of (NH₄)₂Sₓ was shown to be an effective way to substantially lower AlGaAs surface recombination centers.

In this work, the temperature-dependent characteristics of a sulfur-passivated AlGaAs/InGaAs/GaAs pseudomorphic high-electron-mobility transistor (PHMET) were studied and demonstrated. Sulfur passivation was employed to a gate junction to avoid the difficulty in fabricating high-performance metal/AlGaAs Schottky contacts. The passivation method controls defective states originating from (i) air oxidation of the AlGaAs surface before Schottky metallization and (ii) interfacial reaction during metallization. In other words, the sulfur passivation effectively reduces the series resistances and interface states. This also indicates that the Fermi-level pinning effect produced by native surface oxides and nonradiative recombination centers can be eliminated. Therefore, good device performance, high-temperature operation capability, and relatively thermally stable characteristics are simultaneously obtained.

Experimental

The epitaxial structure of the studied device was grown on a (100)-oriented semi-insulating (S.I.) GaAs substrate by a metalorganic chemical vapor deposition (MOCVD) system. The layer structure consisted of a 4000 Å GaAs buffer layer, a 200 Å AlAs buffer layer, a 50 Å Al₀.₂₅Ga₀.₇₅As space layer, a δ-doped sheet δ₀(n⁺) = 4 × 10¹⁰ cm⁻², a 400 Å n-Al₀.₂₅Ga₀.₇₅As (n = 3 × 10¹⁷ cm⁻³) Schottky barrier layer, a 300 Å n-GaAs (n = 3 × 10¹⁷ cm⁻³) space layer, and a 500 Å n⁺-GaAs (n⁺ ≈ 3 × 10¹⁸ cm⁻³) cap layer. After epitaxial growth, wet chemical etching, conventional vacuum evaporation, and lift-off techniques were used to fabricate mesa-type devices. Drain-source ohmic contacts were formed on the n⁺-GaAs cap layer by alloying evaporated AuGeNi/Au metals at 430°C for 3 min. Then n⁺-GaAs cap and n-GaAs space layers were removed and the sample (device A) was immediately passivated by soaking in the ammonium–sulfide [(NH₄)₂Sₓ, 5%] solution for 10 min at room temperature. After surface passivation, the sample was rinsed in deionized (DI) water, followed by blown-dry N₂ gas. This procedure was used to remove thin, whitish residual amorphous sulfur on the surfaces of AlGaAs and ohmic contact metal. For comparison, another device (denoted device B) prepared with the same process only without (NH₄)₂Sₓ treatment was also included in this work. Finally, the gate Schottky contacts were achieved by evaporating Pt/Au metals on the n-Al₀.₂₅Ga₀.₇₅As Schottky barrier layer with the gate dimension of 1 × 100 μm². The experimental dc current–voltage (I–V) characteristics were measured by an HP4156A semiconductor parameter analyzer. The microwave performances of the studied devices were measured by an HP8510C network analyzer in conjunction with Cascade probes at different temperature. During the process, device characteristics are monitored systematically to assure that the process is reproducible.

Results and Discussion

Figure 1 shows forward turn-on voltage (V₉₅), gate-drain breakdown voltage (BV₂D), and reverse gate leakage current (I₉₅) as a function of temperature. The V₉₅, BV₂D, and I₉₅ were measured under the gate current of 1 mA/mm, −0.5 mA/mm, and the gate-drain voltage of V₂D = −22 V, respectively. For device A (with sulfur passivation) and B (without sulfur passivation), the V₉₅ values were decreased from 0.994 to 0.69 V and 0.936 to 0.598 V, respectively, as the temperature was increased from 300 to 510 K. The corresponding BV₂D were decreased from 36.4 to 21.5 V and 32.4 to 16.9 V, while the corresponding I₉₅ values were increased from 0.6 to 571 μA/mm and 7 to 1830 μA/mm. The I₉₅ of device B was several times higher than that of device A. This indicates that the high density defects were produced near the AlGaAs interface of device B, which caused the increases of nonradiative recombination centers and surface leakage current. Thus, the Schottky and breakdown characteristics deteriorated. The properties of V₉₅, BV₂D, and

E-mail: wcliu@mail.ncku.edu.tw

© 2006 The Electrochemical Society. [DOI: 10.1149/1.2199433] All rights reserved.

Manuscript submitted February 23, 2006; revised manuscript received March 16, 2006. Available electronically May 10, 2006.
The $I_G$ of device A were remarkably improved over a wide temperature range (300–510 K). This may be due to DI water rinsing after the (NH$_4$)$_2$S$_x$ treatment, which helped to remove the deposited sulfur in the forms of sulfate and polysulfur. This is a crucial process to reduce the surface leakage current. In addition, the temperature degradation rates in $V_{on}$, $BV_{GD}$, and $I_G$ values were only −1.46 mV/K, −66.1 mV/K, and 2.02 A/mm K, respectively, as the temperature was increased from 300 to 510 K. The corresponding temperature degradation rates of device B were −1.60 mV/K, −68.9 mV/K, and 7.14 A/mm K, respectively. Device A still maintained high $V_{on}$, high $BV_{GD}$, and low $I_G$ values at higher temperature regimes, implying that the sulfur passivation can reduce the generation of leakage current resulting from the increase of temperature. Therefore, the sulfur-passivated device exhibited improved thermal stability of metal/AlGaAs Schottky contact among a wide range of operating temperatures.

Figure 2a–c shows typical common-source I–V characteristics of the studied devices at 300, 390, and 510 K. The applied gate-source voltage was kept at $V_{GS} = −0.5$ V/step. Device A shows good pinch-off and saturation characteristics with high transconductance and without significant gate leakage current, even at a higher temperature of 510 K. This implies that the high breakdown voltage associated with good Schottky behavior and carrier confinement effect is obtained in device A. Besides, the drain saturation current ($I_{DS}$) of device A (B), measured at $V_{DS} = 3.5$ V and $V_{GS} = ±1.0$ V, were 523 (497), 485 (460), and 433 (392) mA/mm at 300, 390, and 510 K, respectively. The deviations of $I_{DS}$ were 17.2 and 21.1% for device A and B as the temperature was increased from 300 to 510 K. Obviously, the degradation of $I_{DS}$ values caused by the increase of temperature is relatively insignificant in device A. Because the sulfur-passivated device has more stable group III elements without dangling bonds on the AlGaAs surface, this certainly suppressed the interface traps and reduced the leakage current over operating temperatures ranging from 300 to 510 K. Therefore, based on the (NH$_4$)$_2$S$_x$ treatment, the studied device is certainly suitable for high-temperature applications.

The maximum extrinsic transconductance ($g_{m,max}$) and on-resistance ($R_{on}$) as a function of temperature are illustrated in Fig. 3. $R_{on}$ is determined from the slope of the linear region by the extrapolation of $I_{DS}$ vs $V_{DS}$ curves. The $g_{m,max}$ value of device A (B) was decreased from 240 (179) to 211 (154) mS/mm as the temperature was increased from 300 to 510 K. On the contrary, the correspond-
shows the device A at different temperatures are depicted in Fig. 4. The inset and peak value. The width of the $R_g$ coefficient in temperature was defined as the $I_{ds}$, $R_p$ from 348 to 510 K. This proves that the studied device with characteristics in terms of $I_{ds}$, and normalized $g_{m,max}$ on the stress time, under stress conditions of $V_{DS} = 7.0$ V and $V_{GS} = 0$ V at 360 K, are shown in Fig. 5. The $I_{ds}$ and $g_{m,max}$ values decrease and then nearly maintain at the same magnitude as the stress time increases. After 188 h of stress testing, the variations of $I_{ds}$ ($g_{m,max}$) for devices A and B were lower than 2.2 (2.8)% and 4.4 (5.5)% respectively. This implies that the $(NH_2)_2S$ treatment is effective in eliminating the interface state formation at the metal/AlGaAs Schottky contact and protecting the AlGaAs surface from oxidation. Therefore, the sulfur-passivated device exhibits relatively temperature-independent and thermal stability characteristics in terms of $I_{ds}$ and $g_{m,max}$. Figure 6 reveals the unity current gain cutoff frequency ($f_T$), maximum oscillation frequency ($f_{max}$), and $I_{ds}$ operating regime ($>0.8$ maximum values of $f_T$, $f_{max}$) as a function of temperature. The inset shows microwave characteristics of device A at 300, 350, and 400 K. The biased voltages were fixed at $V_{DS} = 3.5$ (3.5) V and properties of amplification performance are achieved, even if the temperature was elevated to 510 K. In addition, the dependencies of normalized $I_{ds}$ and normalized $g_{m,max}$ on the stress time, under stress conditions of $V_{DS} = 7.0$ V and $V_{GS} = 0$ V at 360 K, are shown in Fig. 5. The $I_{ds}$ and $g_{m,max}$ values decrease and then nearly maintain at the same magnitude as the stress time increases. After 188 h of stress testing, the variations of $I_{ds}$ ($g_{m,max}$) for devices A and B were lower than 2.2 (2.8)% and 4.4 (5.5)% respectively. This implies that the $(NH_2)_2S$ treatment is effective in eliminating the interface state formation at the metal/AlGaAs Schottky contact and protecting the AlGaAs surface from oxidation. Therefore, the sulfur-passivated device exhibits relatively temperature-independent and thermal stability characteristics in terms of $I_{ds}$ and $g_{m,max}$.

Figure 6 reveals the unity current gain cutoff frequency ($f_T$), maximum oscillation frequency ($f_{max}$), and $I_{ds}$ operating regime ($>0.8$ maximum values of $f_T$, $f_{max}$) as a function of temperature. The inset shows microwave characteristics of device A at 300, 350, and 400 K. The biased voltages were fixed at $V_{DS} = 3.5$ (3.5) V and properties of amplification performance are achieved, even if the temperature was elevated to 510 K. In addition, the dependencies of normalized $I_{ds}$ and normalized $g_{m,max}$ on the stress time, under stress conditions of $V_{DS} = 7.0$ V and $V_{GS} = 0$ V at 360 K, are shown in Fig. 5. The $I_{ds}$ and $g_{m,max}$ values decrease and then nearly maintain at the same magnitude as the stress time increases. After 188 h of stress testing, the variations of $I_{ds}$ ($g_{m,max}$) for devices A and B were lower than 2.2 (2.8)% and 4.4 (5.5)% respectively. This implies that the $(NH_2)_2S$ treatment is effective in eliminating the interface state formation at the metal/AlGaAs Schottky contact and protecting the AlGaAs surface from oxidation. Therefore, the sulfur-passivated device exhibits relatively temperature-independent and thermal stability characteristics in terms of $I_{ds}$ and $g_{m,max}$.
device A is relatively insignificant as the temperature is increased.

The forward turn-on voltage of 0.994 V, gate leakage current of 0.6 (571) μA/mm at $V_{GD} = -22$ V, maximum transconductance of 209 (159) mS/mm, on-resistance of 2.6 (3.7) Ω mm, and linear operating regime of 348 (242) mA/mm were obtained, respectively, at 300 (510) K. The corresponding microwave properties of $f_T$ and $f_{max}$ are 21.2 (19.5) and 73.4 (59.3) GHz at 300 (400) K, respectively. Moreover, the degradation of device performance with the increase of temperature are insignificant. Therefore, the studied device provides the promise for high-temperature and high-performance microwave applications.

Acknowledgments

Part of this work was supported by the National Science Council of the Republic of China under contract no. NSC-94-2215-E-006-060 and no. 94-2215-E-197-002. The authors are also grateful to National Nano Device Laboratories (NDL) for radio frequency measurements.

National Cheng Kung University assisted in meeting the publication costs of this article.

References