Threshold voltage control by gate oxide thickness in fluorinated GaN metal-oxide-semiconductor high-electron-mobility transistors

Yuhao Zhang, Min Sun, Sameer J. Joglekar, Tatsuya Fujishima, and Tomás Palacios

Citation: Appl. Phys. Lett. 103, 033524 (2013); doi: 10.1063/1.4815923
View online: https://doi.org/10.1063/1.4815923
View Table of Contents: http://aip.scitation.org/toc/apl/103/3
Published by the American Institute of Physics

Articles you may be interested in

A comprehensive analytical model for threshold voltage calculation in GaN based metal-oxide-semiconductor high-electron-mobility transistors
Applied Physics Letters 100, 113509 (2012); 10.1063/1.3694768

Trench formation and corner rounding in vertical GaN power devices
Applied Physics Letters 110, 193506 (2017); 10.1063/1.4983558

Characterization of interface states in Al2O3/AlGaN/GaN structures for improved performance of high-electron-mobility transistors
Journal of Applied Physics 114, 244503 (2013); 10.1063/1.4859576

Two-dimensional electron gases induced by spontaneous and piezoelectric polarization charges in N- and Ga-face AlGaN/GaN heterostructures
Journal of Applied Physics 85, 3222 (1999); 10.1063/1.369664

Polarization effects, surface states, and the source of electrons in AlGaN/GaN heterostructure field effect transistors
Applied Physics Letters 77, 250 (2000); 10.1063/1.126940

On the physical operation and optimization of the p-GaN gate in normally-off GaN HEMT devices
Applied Physics Letters 110, 123502 (2017); 10.1063/1.4978690
Threshold voltage control by gate oxide thickness in fluorinated GaN metal-oxide-semiconductor high-electron-mobility transistors

Yuhao Zhang,* Min Sun, Sameer J. Joglekar, Tatsuya Fujishima, and Tomás Palacios
Microsystems Technology Laboratories, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

(Received 26 March 2013; accepted 18 June 2013; published online 19 July 2013)

This paper demonstrates the compensation of the intrinsic positive charges in Al2O3 gate dielectric by fluorine ions in GaN metal-oxide-semiconductor high-electron-mobility transistors (MOS-HEMTs). Negatively-charged fluorine ions diffused into the oxide from the AlGaN barrier during the 250 °C atomic layer deposition compensate the intrinsic positive charge present in the Al2O3. This compensation is key to control the threshold voltage (Vth) of enhancement-mode (E-mode) transistors. A comprehensive analytical model for the Vth of fluorinated MOS-HEMTs was established and verified by experimental data. This model allows the calculation of the different charge components in order to optimize the transistor structure for E-mode operation. Using the proposed charge compensation, the Vth increases with gate dielectric thickness, exceeding 3.5 V for gate dielectrics 25 nm thick. © 2013 AIP Publishing LLC. [http://dx.doi.org/10.1063/1.4815923]
diameter of 180 \( \mu m \) were fabricated in the same sample. In addition to the fluorinated devices, transistors and diodes with identical geometry and layer but without the fluorination step were also fabricated as a reference (standard).

Figures 2(a) and 2(b) show the transfer characteristics of standard and 150 s-plasma-treated MOS-HEMTs with different gate oxide thickness. In the literature, many different methods to extract the threshold voltage have been proposed, including transconductance extrapolation and current extrapolation under linear and saturation operating conditions. However, these methods could suffer from uncertainties, since the current or transconductance characteristics can deviate from ideal straight line behavior in the threshold region.

Thus, in this work, a constant-current method, widely used for MOSFETs and HEMTs, was adopted to extract and compare the \( V_{th} \) of different devices. Here, the \( V_{th} \) is defined as the gate voltage when drain current reaches \( 10 \mu A/mm \) at \( V_{ds} = 1 \) V in the subthreshold region. The transistor \( V_{th} \) defined in this way was found to be independent of \( V_{ds} \) (measured from \( V_{ds} = 1 \) V to \( V_{ds} = 10 \) V) and consistent with the capacitance turn-around point extracted from \( C-V \) curves of MOS diodes (A typical \( C-V \) curve of the fluorinated MOS diodes is shown in Figure 4(a)).

The \( V_{th} \) of MOS-HEMTs as a function of oxide thickness for four fluorine treatment times (0, 150, 160, and 170 s) is summarized in Figure 3. As can be seen, a \( V_{th} \) that increases with gate oxide thickness was achieved for fluorinated MOS-HEMTs. This is opposite to the behavior of E-mode devices fabricated through gate recess, where the \( V_{th} \) hardly increases as the gate dielectric thickness is increased due to the fixed positive charges in \( Al_2O_3 \).

The \( V_{th} \) dependence with oxide thickness and fluorine time in the fluorinated devices is far from linear, indicating a comprehensive analytical \( V_{th} \) model, including different charges and fluorine effect quantitatively is needed. By modifying the electrostatic \( V_{th} \) model for a standard MOS-HEMT, the \( V_{th} \) for fluorinated MOS-HEMTs can be expressed as

\[
V_{th} = \frac{\Phi_b}{q} - \frac{qE_c}{q} - \frac{qF_t}{q} - \frac{q^2}{2\varepsilon_{ox}} - \frac{q^2}{\varepsilon_{ox}} Q_{Al_2O_3/AlGaN} - \frac{q^2}{\varepsilon_{AlGaN}} Q_{AlGaN/GaN} - q\phi_{Fluorine},
\]

where \( \Phi_b \) is the metal barrier height for Ni on \( Al_2O_3 \) (i.e., 3.5 eV), \( E_c \) is the conduction band offset between \( Al_2O_3 \) and GaN (i.e., 2.1 eV), \( F_t \) is the conduction band distance from the Fermi-level in GaN (~0.2 eV), \( t \) is the thickness, \( \varepsilon \) is the permittivity, and the subscripts \( ox \) and \( b \) refer to the oxide and barrier layer (AlGaN), respectively. \( \varepsilon_{ox} \) is the average oxide bulk charge (per unit volume). \( Q_{Al_2O_3/AlGaN} \) and \( Q_{AlGaN/GaN} \) are the interface charge density at the \( Al_2O_3/AlGaN \) interface (more details below) and the AlGaN/GaN-channel interface (+7 \( \times 10^{12} \) cm\(^{-2} \), estimated by gated-Hall measurements of the 2-DEG sheet charge density).

\( q\phi_{Fluorine} \) is the conduction band shift induced by the fluorine plasma treatment. It has been reported that the main contributing factor to this band shift is not the change in the surface potential, but rather the negative fixed charges due to fluorine ions inside AlGaN/GaN heterostructures. In this
work, $\Phi_{\text{Fluorine}}$ is assumed to be the result of only negative fluorine charges. If we set the origin of the $x$ axis ($x = 0$) at the Al$_2$O$_3$/AlGaN interface as shown in Figure 1(b), then $\Phi_{\text{Fluorine}}$ can be expressed as

$$\Phi_{\text{Fluorine}} = \int_0^{t_0} \left( \frac{t_0}{e_{\text{AlGaN}}} + \frac{x}{e_{\text{AlGaN}}} \right) n_p(x) dx + \int_{t_0}^{t_0+\alpha_{\text{AlGaN}}} \left( \frac{t_0}{e_{\text{AlGaN}}} + \frac{t_b}{e_{\text{GaN}}} + \frac{x}{e_{\text{GaN}}} \right) n_p(x) dx = \frac{q_{\text{tox}}}{e_{\text{tox}}} n_F(x) dx + \varphi(F) = \frac{q_{\text{tox}}}{e_{\text{tox}}} Q(F) + \varphi(F),$$

(2)

where $n_p(x)$ is the effective fluorine negative charge density (per unit volume) in the AlGaN and GaN; $Q(F)$ is defined as a fluorine equivalent interface charge (per area) located at the AlGaN/Al$_2$O$_3$ interface calculated by integration of the fluorine negative charge in the bulk GaN and AlGaN; $q_0(F)$ is defined as a constant band bending dependent only on density of fluorine charge and distribution, but independent of the gate oxide thickness. By incorporating Eq. (2) into Eq. (1), we get

$$V_{th} = \frac{\Phi_b}{q} - \frac{\Delta E_c}{q} - \frac{\Phi_f}{q} - \frac{q_{\text{tox}}}{e_{\text{AlGaN}}} Q_{\text{AlGaN/GaN}} - q_0(F)$$

$$- \frac{q}{e_{\text{tox}}} [Q_{\text{AlGaN/GaN}} + Q_{\text{AlGaN/GaN}} + Q(F)] e_{\text{tox}}$$

$$- \frac{q_{\text{tox}}^2}{2e_{\text{tox}}^2}.$$  

(3)

Equation (3) indicates that $V_{th}$ can be described by a quadratic polynomial of the gate oxide thickness $t_{ox}$ with the constant term and the first-order term directly dependent on fluorine plasma time. This relationship was verified by the excellent parabolic fitting achieved to the experimental $V_{th}$ vs. $t_{ox}$ for fluorinated MOS-HEMTs with different fluorine plasma time, as shown in Figure 3. On the other hand, a similar analytical model without the fluorine-related terms was adopted to fit the experimental results on standard MOS-HEMTs. An excellent agreement between model and experiments was also achieved in this case, as shown in Figure 3. The schematic charge distribution and energy band diagram of the fluorinated MOS-HEMTs were shown in Figure 4. The fluoride-induced band bending $q_0(F)$, total equivalent Al$_2$O$_3$/nitride interface charges ($Q_{\text{AlGaN/GaN}} + Q(F)$) for fluorinated MOS-HEMTs and $Q_{\text{AlGaN/GaN}}$ for standard MOS-HEMTs and average oxide bulk charge $\pi_{\text{ox}}$ derived from fitting the model to the experimental results are summarized in Table I.

As shown in Table I, a large positive charge $Q_{\text{AlGaN/GaN}}$ was found at the oxide/nitride interface in standard MOS-HEMTs, which is consistent with previous reports. In fluorinated MOS-HEMTs, negatively-charged fluorine ions inside the AlGaN/GaN layers, $Q(F)$, compensated the effect of positive interfacial charge, $Q_{\text{AlGaN/GaN}}$, making the equivalent total interfacial charge $Q_{\text{AlGaN/GaN}} + Q(F)$ become negative.

The interface charge ($Q_{\text{AlGaN/GaN}}$ or $Q_{\text{AlGaN/GaN}}$) has three different components: (1) the sum of spontaneous and piezoelectric polarization charges, $Q_F$; (2) the contribution of the negatively charged oxide/AlGaN interfacial traps, $Q_n$; and, (3) the positively-charged ionized

FIG. 3. $V_{th}$ of standard and fluorinated MOS-HEMTs with the gate oxide thickness of 8 nm, 15 nm, 20 nm, and 25 nm by 150 s, 160 s, and 170 s fluorine plasma treatment measured in experiments (dots) and fitted by analytical models (dashed lines).

![FIG. 3.](image)

FIG. 4. (a) Schematic charge distribution in the fluorinated MOS-HEMT based on our analytical models for $V_{th}$ calculation. (b) Energy band diagram of the fluorinated MOS-HEMT calculated by using the TCAD simulator—Silvaco Atlas based on our model.

![FIG. 4.](image)

TABLE I. Fluoride-induced band bending $q_0(F)$, total oxide/silicon interface charges ($Q_{\text{AlGaN/GaN}} + Q(F)$) for fluorinated MOS-HEMTs, $Q_{\text{AlGaN/GaN}}$ for standard MOS-HEMTs, and average bulk oxide charge $\pi_{\text{ox}}$ as a function of fluorine plasma time for fluorinated and standard MOS-HEMTs, as derived from the analytical model.

| Fluorine plasma time (s) | $q_0(F)$ (eV) | $Q_{\text{AlGaN/GaN}} + Q(F)$ ($Q_{\text{AlGaN/GaN}}$) (cm$^{-2}$) | $\pi_{\text{ox}}$ (cm$^{-2}$) |
|-------------------------|--------------|-------------------------------------------------|-----------------------------|
| 0                       | 0            | $7.08 \times 10^{12}$                           | $1.1 \times 10^{18}$       |
| 150                     | 0.4          | $-3.46 \times 10^{12}$                          | $-7.1 \times 10^{18}$      |
| 160                     | 0.7          | $-4.12 \times 10^{12}$                          | $-7.1 \times 10^{18}$      |
| 170                     | 1.0          | $-4.78 \times 10^{12}$                          | $-7.1 \times 10^{18}$      |
surface donors, \( Q_d \). While \( Q_P \) and \( Q_d \) are difficult to separate experimentally, \( Q_d \) can be estimated from the \( C-V \) characterization of MOS capacitors. \(^{10,21,22}\) Figure 5(a) shows the typical \( C-V \) characteristics of standard and plasma-treated MOS capacitors. As can be seen, the hysteresis \( \Delta V_{th} \) in the \( C-V \) curve of fluorinated MOS capacitor is smaller than the hysteresis of a standard MOS capacitor. Using \( Q_d \approx C_{MOS} \cdot \Delta V_{th}/q \), the \( Q_d \) in fluorinated MOS-HEMTs was estimated as \( \sim 2.3 \times 10^{11} \) cm\(^{-2}\), which is one-order of magnitude smaller than the total equivalent interface charges \( Q_{Al_2O_3}/AlGaN + Q(F) \) shown in Table I, indicating that \( Q_d \) is not a major contribution to interface charges. A detailed analysis for the fluorine passivation of interface states will be presented in a future paper.

A constant bulk oxide charge, \( \pi_{ox} \), is sufficient in our model to get excellent agreement with the experimental data for fluorinated MOS-HEMTs. This charge density, \(-7.1 \times 10^{18} \) cm\(^{-3}\), is much more negative than the intrinsic bulk oxide charge density revealed in our standard MOS-HEMTs \((+1.1 \times 10^{18} \) cm\(^{-3}\)) or reported by other groups for ALD-grown \( Al_2O_3 \) on GaN \(^{10}\) and other III-V, \(^{13}\) indicating the presence of additional charges. The SIMS measurements shown in Figure 5(b) indicate that these additional charges are due to fluorine ions diffusing into the gate oxide during the ALD process at 250 °C. The post-gate annealing at 400 °C almost did not change the fluorine distribution in the structure. The fluorine ions passivated the intrinsic positive oxide charges and formed negative charges during high-temperature ALD and annealing possibly by virtue of the strong electronegativity of F. If we use the Gaussian characteristics to approximate the fluorine concentration distribution measured by SIMS, and then the total fluorine ion amount can be integrated and compared with the average bulk oxide charge revealed by our model. In this way, the “activation percentage” of the negatively charged fluorine ions in \( Al_2O_3 \) gate oxide was estimated to be 40–50%. The dynamic and microscopic picture of F-induced charge diffusion and incorporation into the oxide still require a more detailed study.

In conclusion, fluorine ions introduced in the gate dielectric during the ALD deposition compensate the intrinsic positive charge of \( Al_2O_3 \), enabling the accurate control of \( V_{th} \) by changing the gate oxide thickness. A comprehensive analytical model for the \( V_{th} \) modulation was proposed and verified by experimental data to quantitatively study the negative charge introduced in the dielectric by the fluorination process. The proposed fluorine plasma treatment before the ALD gate oxide deposition can be utilized in combination with other E-mode MOS-HEMT technologies, such as gate recess, tri-gate, and band engineering, to compensate the positive charges in the \( Al_2O_3 \) gate dielectric and achieve a more positive \( V_{th} \).

The authors gratefully acknowledge fruitful discussions with Dr. Chang Suh and Dr. David Fanning from TriQuint Semiconductor, Inc., and the funding support of the DARPA MPC program, monitored by Dr. Daniel Green and Dr. Paul Maki.

---

\(^1\) S. G. Khalil, R. Chu, R. Li, D. Wong, S. Newell, X. Chen, M. Chen, D. Zehnder, S. Kim, A. Corrion, B. Hughes, and K. Boutros, in Proceedings of the 42th European Solid-State Device Research Conference, Bordeaux, France, 17–21 Sept. (IEEE, 2012), pp. 310–313.

\(^2\) B. Lu, O. Saadat, and T. Palacios, IEEE Electron Device Lett. 31, 990 (2010).

\(^3\) M. Kanamura, T. Ohki, T. Kikkawa, K. Imanishi, T. Imada, A. Yamada, and N. Harasaka, IEEE Electron Device Lett. 31, 189 (2010).

\(^4\) H. Kambayashi, Y. Satoh, S. Ootomo, T. Kokawa, T. Nomura, S. Kato, and T. P. Chow, Solid-State Electron. 54, 660 (2010).

\(^5\) B. Lu, E. Mattioli, and T. Palacios, IEEE Electron Device Lett. 33, 360 (2012).

\(^6\) C. T. Chang, T. H. Hsu, E. Y. Chang, Y. C. Chen, H. D. Trinh, and K. J. Chen, Electron. Lett. 46, 1280 (2010).

\(^7\) Z. H. Liu, G. I. Ng, S. Arulkumar, Y. K. T. Maung, K. L. Teo, S. C. Foo, and V. Sahnumaganathan, Appl. Phys. Lett. 95, 223501 (2009).

\(^8\) V. Adivarahan, J. Yang, A. Koudymov, G. Simin, and M. A. Khan, IEEE Electron Device Lett. 26, 535 (2005).

\(^9\) R. Wang, Y. Cai, C. W. Tang, K. M. Lau, and K. J. Chen, IEEE Electron Device Lett. 27, 793 (2006).

\(^10\) M. Tapajna and J. Kuzmik, Appl. Phys. Lett. 100, 113509 (2012).

\(^11\) S. Ganguly, J. Verma, G. Li, T. Zimmermann, H. Xing, and D. Jena, Appl. Phys. Lett. 99, 193504 (2011).

\(^12\) M. Esposto, S. Krishnamoorthy, D. N. Nath, S. Bajaj, T. H. Hung, and S. Rajan, Appl. Phys. Lett. 99, 135303 (2011).

\(^13\) B. Shin, J. R. Weber, R. D. Long, P. K. Hurley, C. G. Van de Walle, and P. C. McIntyre, Appl. Phys. Lett. 96, 152908 (2010).

\(^14\) R. Chu, C. S. Suh, M. H. Wong, N. Fichtenbaum, D. Brown, L. McCarthy, S. Keller, F. Wu, J. S. Speck, and U. K. Mishra, IEEE Electron Device Lett. 28, 781 (2007).

\(^15\) R. Chu, L. Shen, N. Fichtenbaum, D. Brown, S. Keller, and U. K. Mishra, IEEE Electron Device Lett. 29, 297 (2008).
16. B. Lu, M. Sun, and T. Palacios, IEEE Electron Device Lett. 34, 369 (2013).
17. A. Ortiz-Condea, F. J. García Sánchez, J. J. Liou, A. Cerdeirac, M. Estrada, and Y. Yue, Microelectron. Reliab. 42, 583 (2002).
18. C. Ma, H. Chen, C. Zhou, S. Huang, L. Yuan, J. Roberts, and K. J. Chen, J. Appl. Phys. 110, 114514 (2011).
19. S. Huang, H. Chen, and K. J. Chen, Appl. Phys. Lett. 96, 233510 (2010).
20. M. Fagerlind, F. Allerstam, E. Ö. Sveinbjörnsson, N. Rorsman, A. Kakanakova-Georgieva, A. Lundskog, U. Forsberg, and E. Janzén, J. Appl. Phys. 108, 014508 (2010).
21. C. Mizue, Y. Hori, M. Miczek, and T. Hashizume, Jpn. J. Appl. Phys. Part 1 50, 021001 (2011).
22. S. Huang, S. Yang, J. Roberts, and K. J. Chen, Jpn. J. Appl. Phys. Part 1 50, 110202 (2011).