Enhanced Off-State Leakage Currents in n-Channel MOSFET's with N_2O-Grown Gate Dielectric

Zeng Xu, P. T. Lai, *Member, IEEE*, and W. T. Ng, *Member, IEEE*

***Abstract*—This paper reports on the off-state drain (GIDL) and gate current (I_g) characteristics of n-channel MOSFET's using thin thermal oxide (OX), N_2O-nitrided oxide (N2ON), and N_2O-grown oxide (N2OG) as gate dielectrics. Important phenomena observed in N2OG devices are enhanced GIDL and I_g in the low-field region as compared to the OX and N2ON devices. They are attributed to heavy-nitridation-induced junction leakage and shallow-electron-trap-assisted tunneling mechanisms, respectively. Therefore, N2ON oxide is superior to N2OG oxide in leakage-sensitive applications.**

I. Introduction

Gate-induced drain leakage (GIDL) and off-state gate current (I_g) in thermal oxide [1]–[4] and NH_3-nitrided gate oxide (NO) [5] have been studied previously. Band-to-band (B-B) tunneling in the low-field regime and avalanche effect in the high-field region have been identified to be the origin of GIDL [1]–[3]. The I_g in conventional thermal oxide n-channel MOSFET's has been attributed to Fowler–Nordheim (F–N) tunneling of electrons from the gate for SiO_2 thinner than 100 Å, and to hot-hole injection from the drain for thicker oxide [4]. In [5], hot-hole injection model and nitridation-induced barrier height lowering effect were used to account for the enhanced I_g in NO n-channel MOSFET's. On the other hand, an N_2O-based nitridation technology has been intensively studied recently as a more promising alternative to NH_3-nitridation because of its simpler processing and the absence of detrimental hydrogen-related species in the nitridation ambient [6]–[9]. Nevertheless, the off-state gate current characteristics in MOSFET's with N_2O-based gate oxide has not yet been reported in literature, and this work attempts to shed some light on this aspect.

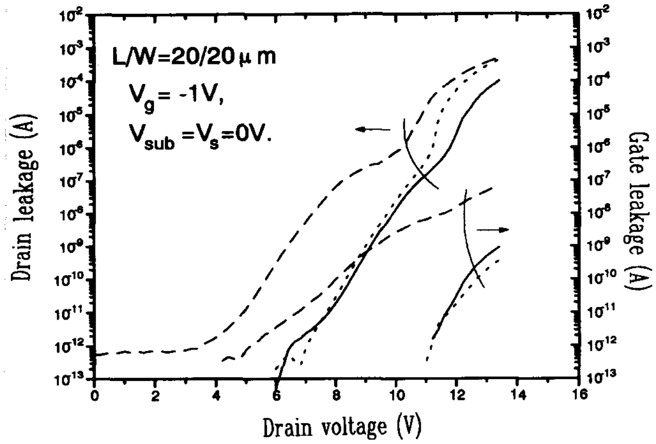

Fig. 1. Drain and gate leakage currents for OX (solid lines), N2ON (dotted lines), and N2OG (dashed lines) devices.

II. Experimental

The n-MOSFET's used in this study were fabricated on p-type (100) Si wafer (6 ~ 8 Ω-cm) using self-aligned n^+ poly-Si gate process. Following LOCOS active area definition, channel doping ($\sim 2 \times 10^{17}$ cm^{-3}) was controlled by boron implant through a sacrificial oxide. Then, three kinds of gate dielectrics were prepared: Thermal oxide grown at 850°C for 70 min in dry O_2 was used as control samples (OX). N_2O-nitrided oxide (N2ON) was formed by first grown at 850°C for 60 min in dry O_2 and then annealed in N_2O at 950°C for 20 min. A 120 min growth at 950°C in pure N_2O ambient was used to fabricate N_2O-grown oxide (N2OG). The oxide-growth conditions are chosen in such a way that the final thickness of all gate dielectrics is around 140 Å as measured by CV techniques. No passivation film was used. Since off-state leakage is independent of channel length, devices with larger dimensions (L/W = 20 μm/20 μm) were adopted in this work to prevent possible punch-through during measurement and to minimize fringe effect.

III. Results and Discussion

Fig. 1 shows the GIDL and corresponding I_g characteristics of n-MOSFET's with OX, N2ON and N2OG gate dielectrics. Two important observations are found. First, N2OG device shows enhanced GIDL as compared to other devices. This can be ascribed to junction leakage resulted from heavy nitridation when gate oxide is grown in N_2O [10]. Second, in the low-field region ($V_d = 5 \sim 10$ V), where the drain leakage is dominated by B-B tunneling at drain corner, an exponentially V_d-dependent I_g is observed in N2OG devices only, as shown in Fig. 1. In contrast, no detectable I_g is found in this V_d region for OX and N2ON devices and I_g only appears in the high V_d region (>11 V), where avalanche effect occurs at drain junction. F-N tunneling of electrons from n^+ poly-gate through the gate dielectric cannot account for the observed low-field I_g in N2OG device because the slope of the F-N plot for the N2OG device in low-field region, depicted in Fig. 2 ($E_{ox}^{-1} = 0.17 \sim 0.30$ cm/MV), is much

---

Manuscript received April 27, 1995.

Z. Xu and P. T. Lai are with the Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong.

W. T. Ng is with the Department of Electrical and Computer Engineering, University of Toronto, Toronto, Ontario, Canada M5S 1A4.

IEEE Log Number 9414355.

0741-3106/95$04.00 © 1995 IEEE

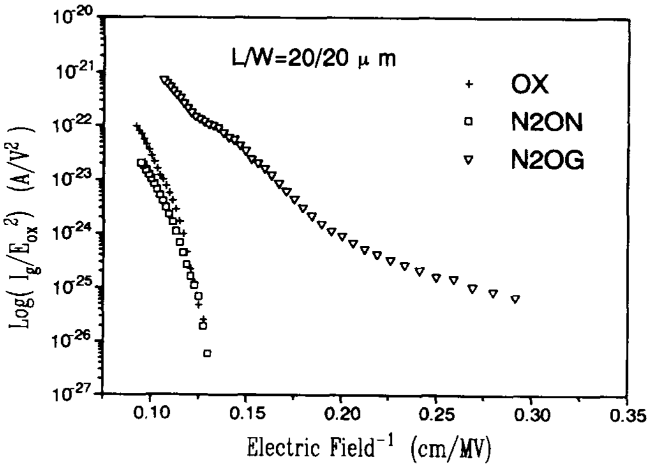

Fig. 2. F-N plots for the off-state gate current in the OX, N2ON, and N2OG n-MOSFET's.

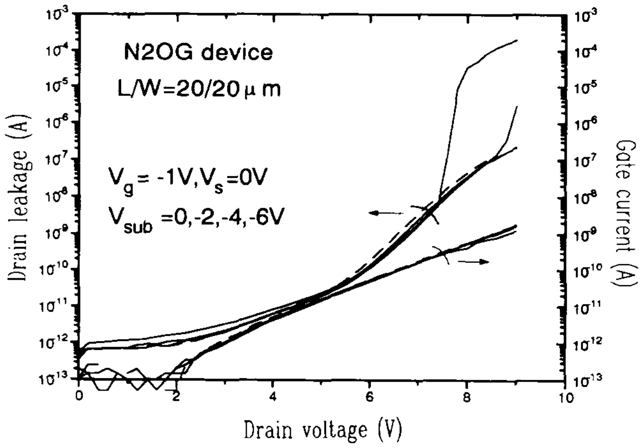

Fig. 3. Drain and gate leakage currents at $V_{sub} = 0, -2, -4, -6$ V (from right to left) in N2OG device.

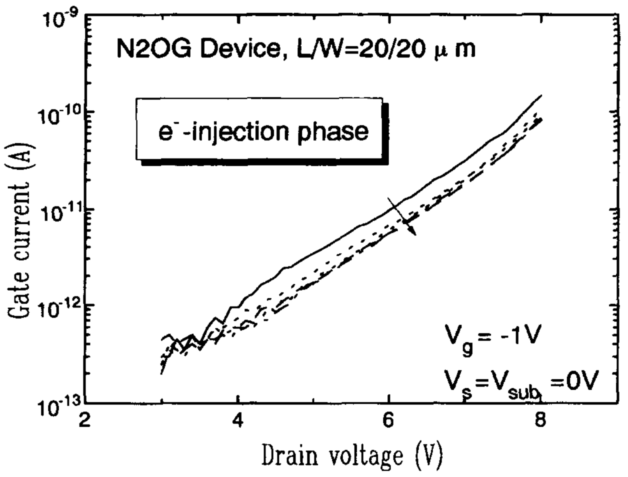

Fig. 4. Off-state gate current measured at stress time = 0, 50, 400, 2200, and 4000 s (in the arrow direction). Hot-electron stress condition: $V_g = 7.5$ V, $V_d = 7.0$ V, $V_s = V_{sub} = 0$ V.

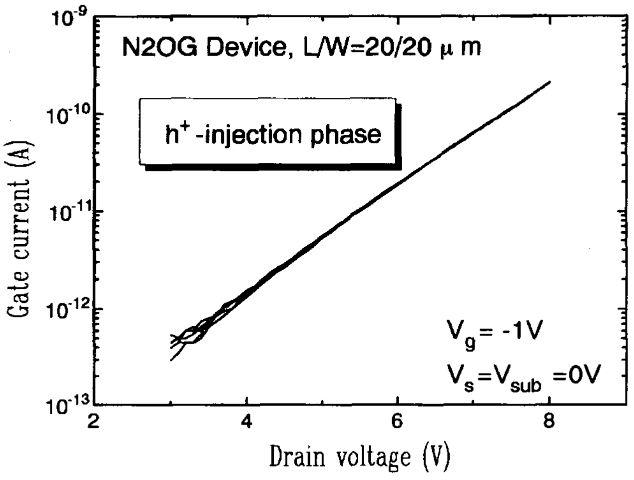

Fig. 5. Off-state gate current measured at stress time = 0, 50, 400, 2200, and 4000 s (in the arrow direction). Hot-hole stress condition: $V_g = 0.7$ V, $V_d = 7.0$ V, $V_s = V_{sub} = 0$ V.

smaller than normal values, which would yield physically unreasonable low barrier height for the gate dielectric. In fact, studies performed on MOS capacitors have indicated that the barrier height against electron-injection for N_2O-grown oxides is similar to that in pure SiO_2 [9]. Mechanism of hot-hole injection from the drain to the gate [5] also cannot be responsible for the observed low-field I_g, even if nitridation-induced barrier-height lowering effect is taken into account. To verify such a claim, we measured the off-state drain and gate leakage currents of N2OG device under four different substrate biases. The results are given in Fig. 3. It can be clearly seen that although drain leakage is strongly affected by the avalanche effect at the drain-substrate junction, indicating hot-hole trapping in gate oxide, the corresponding I_g remains unchanged for all V_{sub} values, suggesting that I_g cannot be attributed to hot-hole injection. On the other hand, the model of shallow-trap-assisted tunneling of electrons from the gate [11] can readily explain the low-field I_g observed in N2OG devices. This argument is supported below by channel hot-carrier stress experiments. Presented in Fig. 4 is the measured I_g after different stress time of channel hot-electron injection. I_g decreases as the electron injection and trapping proceed because electron traps in the gate oxide are filled up by the injected electrons. This behavior is contrary to the hot-hole injection model, since electron trapping should lead to increasing I_g due to electric field enhancement at the drain corner. Experiment of hot-hole injection effect on I_g, shown in Fig. 5, further confirms the trap-assisted tunneling mechanism. Off-state I_g is not affected during the whole hot-hole injection stress since the gate current conduction is essentially not related to the holes but electrons only. A possible explanation for the absence of shallow-trap-assisted tunneling in the N2ON samples is that the growth kinetics for N_2O-grown and N_2O-nitrided oxides are different in the initial period [12]. For the N_2O-grown oxides, there exists an initial accelerated growth phase before the linear growth region. This rapid growth can generate lots of defects, such as shallow electron traps in the N2OG oxide, which trigger the observed low-field gate leakage. While for the N_2O-nitrided oxides, the initial accelerated growth phase does not exist, especially when the initial oxide thickness is larger than around 50 Å (e.g., our N2ON samples).

IV. SUMMARY

Off-state gate current of n-channel MOSFET's with OX, N2ON, and N2OG oxides as gate dielectrics was investigated in this work. It is revealed that gate current conduction mechanism in low-field region is very different for these oxides. Enhanced conductivity is observed in N2OG oxides, which is attributed to the trap-assisted tunneling mechanism. Therefore, the method of nitridizing pre-grown thermal oxide (N2ON) is more feasible than directly growing oxide in N_2O ambient (N2OG) in view of the drain and gate leakage currents, especially in leakage-sensitive applications, such as very-low-power battery-based circuits, DRAM cells, and the like.

REFERENCES

[1] C. Chang and J. Lien, "Cornor-field induced drain leakage in thin oxide MOSFET's," *IEDM Tech. Dig.*, p. 714, 1987.

[2] T. Y. Chan, J. Chen, P. K. Ko, and C. Hu, "The impact of gate-induced drain leakage current on MOSFET scaling," *IEDM Tech. Dig.*, p. 718, 1987.

[3] C. Chang, S. Haddad, B. Swaminathan, and J. Lien, "Drain-avalanche and hole-trapping induced gate leakage in thin-oxide MOS devices," *IEEE Electron Device Lett.*, vol. 9, p. 588, 1988.

[4] J. Chen, T. Y. Chan, P. K. Ko, and C. Hu, "Gate current in off-state MOSFET," *IEEE Electron Device Lett.*, vol. 10, no. 5, p. 203, 1989.

[5] A. T. Wu, S. H. Lee, V. Murali, and M. Garner, "Off-state gate current in n-channel MOSFET's with nitrided oxide gate dielectrics," *IEEE Electron Device Lett.*, vol. 11, p. 499, 1990.

[6] A. Uchiyama, H. Fukuda, T. Hayashi, T. Iwabuchi, and S. Ohno, "High-performance dual-gate sub-halfmicron CMOSFET's with 6-nm-thick nitrided SiO_2 films in an N_2O ambient," in *IEDM Tech. Dig.*, p. 425, 1990.

[7] H. Hwang, W. Ting, D.-L. Kwong, and J. Lee, "Electrical and reliability characteristics of ultrathin oxynitride gate dielectric prepared by rapid thermal processing in N_2O," *IEDM Tech. Dig.*, p. 421, 1990.

[8] Z. H. Liu, H. J. Wann, P. K. Ko, C. Hu, and Y. C. Cheng, "Effects of N_2O anneal and reoxidation on thermal oxide characteristics," *IEEE Electron Device Lett.*, vol. 13, p. 402, 1992.

[9] A. B. Joshi, G. Yoon, J. Kim, G. Q. Lo, and D.-L. Kwong, "High-field breakdown in thin oxides grown in N_2O ambient," *IEEE Trans. Electron Devices*, vol. 40, p. 1437, 1993.

[10] A. Ditali, V. Mathews, and P. Fazan, "Hot-carrier-induced degradation of gate dielectrics grown in nitrous oxide under accelerated aging," *IEEE Electron Device Lett.*, vol. 13, p. 538, 1992.

[11] H. Wong and Y. C. Cheng, "Electronic conduction mechanisms in thin oxynitride films," *J. Appl. Phys.*, vol. 70(2), p. 1078, 1991.

[12] H. R. Soleimani, A. Philipossian, and B. Doyle, "A study of the growth kinetics of SiO_2 in N_2O," *IEDM Tech. Dig.*, p. 629, 1992.