Improved Performance and Reliability of N_2O-Grown Oxynitride on 6H-SiC

J. P. Xu, P. T. Lai, C. L. Chan, B. Li, and Y. C. Cheng

***Abstract*—This letter reports, for the first time, N_2O-grown oxides on both n-type and p-type 6H-SiC wafers. It is demonstrated that the N_2O-grown technique leads to not only greatly improved SiC/SiO_2 interface and oxide qualities, but also considerably enhanced device reliabilities as as compared to N_2O-nitrided and conventional thermally-oxidized devices. These improvements are especially obvious for p-type SiC MOS device, indicating that N_2O oxidation could be a promising technique for fabricating enhancement-type n-channel SiC MOSFET's.**

***Index Terms*—Hot-carrier stress, MOS devices, MOSFETs, nitridation, SiC.**

I. Introduction

One OF the most important advantages of silicon carbide (SiC) over other wide-bandgap semiconductors is that it can be thermally oxidized to form SiO_2. However, it has been frequently reported that oxides grown on SiC have high interface- state density and a large amount of fixed oxide charges, especially for the SiO_2/p-SiC structure [1], [2]. Recently, NO and N_2O nitridation techniques have been used to improve the interface and oxide qualities [3], [4], and it is successful for NO-nitrided MOS devices. Unfortunately, it is found that N_2O nitridation deteriorates the electrical properties of devices. Interestingly in this work, an attractive method involving N_2O to effectively overcome the above problems is developed. For the first time, N_2O-grown technique used for Si MOSFET's is successfully applied to SiC MOS devices, and considerable improvements are obtained in not only SiO_2/SiC interface and oxide qualities, but also device reliability. Relevant results on N_2O-grown MOS capacitors are reported, suggesting that a high-quality and high-reliability SiO_2–SiC system could be realized by this N_2O-grown technology, even on p-type SiC substrate.

II. Experiments

N- and p-type (0001) Si-face 6H-SiC wafers, manufactured by CREE Research, were used in this study. The SiC wafers had a 5-μm epitaxial layer grown on heavily doped substrates. The doping level of the epitaxial layer of the two types of wafers was 4×10^{15} cm^{-3}. The wafers were cleaned using the conventional RCA method followed by a 60-s dipping in 1% HF, and then loaded into a quartz furnace at 850 °C. After raising to an oxidation temperature of 1100 °C, a 360-min oxidation was carried out in pure N_2O ambient (denoted as N2OG sample). N- and p-type control samples were thermally oxidized in a wet O_2 ambient by bubbling oxygen through de-ionized water at 95 °C at the same temperature for 150 min (denoted as OX sample), because wet oxide is known to have better qualities than dry oxide [5], [6]. For the purpose of comparison, some n- and p-type OX samples were nitrided in pure N_2O ambient at 1100 °C for 1.5 h (denoted as N2ON sample). Then the three kinds of samples were annealed in N_2 at 1100 °C for 1 h. Finally, aluminum was thermally evaporated, and then patterned as gate electrode of MOS capacitors (area was 1.8×10^{-4} cm^2), followed by a forming gas anneal at 410 °C for 30 min. High-field stress (±7 MV/cm), with the capacitor biased in accumulation, was used to examine device reliability. For comparing with the wet oxides, two other n-type wafers were oxidized in dry O_2 at the same temperature, but for a longer time of 3.5 h to get the same oxide thickness (denoted as DRY sample). One of them then went through the same N_2O nitridation as the wet samples. The SiO_2/SiC interface and oxide properties were characterized by flat-band voltage, oxide charge and their changes after stressing which were extracted from high-frequency (HF) capacitance–voltage (*C*–*V*) measurements at room temperature under dark condition. All measurements were carried out under a light-tight and electrically shielded condition.

III. Results and Discussions

Fig. 1 shows the typical HF *C*–*V* curves of all the samples under dark condition, swept in both directions, and no appreciable hysteresis occurs, implying little slow traps in the oxides. For n-type substrate, N2OG and N2ON samples exhibit slightly improved flat-band behavior relative to OX sample, with N2OG sample closest to the ideal *C*–*V* curve (flat-band voltages V_{fb} is almost 0 V). Obviously for p-type substrate, N_2O nitridation deteriorates the *C*–*V* properties of the device and a large difference between the two *C*–*V* curves for different sweep directions occurs, in consistent with the results in [3]. On the other hand, N_2O-grown sample exhibits an improved *C*–*V* behavior as compared to OX sample. Some parameters extracted from the HF–*C*–*V* curves are summarized in Table I. The oxide thickness t_{ox} is calculated from the HF accumulation capacitance or oxide capacitance C_{ox}. V_{fb} is determined from the flat-band capacitance C_{fb} [7]

$$\frac{C_{fb}}{C_{ox}} = \left(1 + \frac{136\sqrt{T/300}}{t_{ox}\sqrt{N}}\right)^{-1} \quad (1)$$

Manuscript received September 6, 1999; revised February 29, 2000. This work was supported by the RGC and CRCG Research Grants, University of Hong Kong. The review of this letter was arranged by Editor D. J. Dumin.

J. P. Xu is with the Department of Solid State Electronics, Huazhong University of Science and Technology, Wuhan, 430074, China.

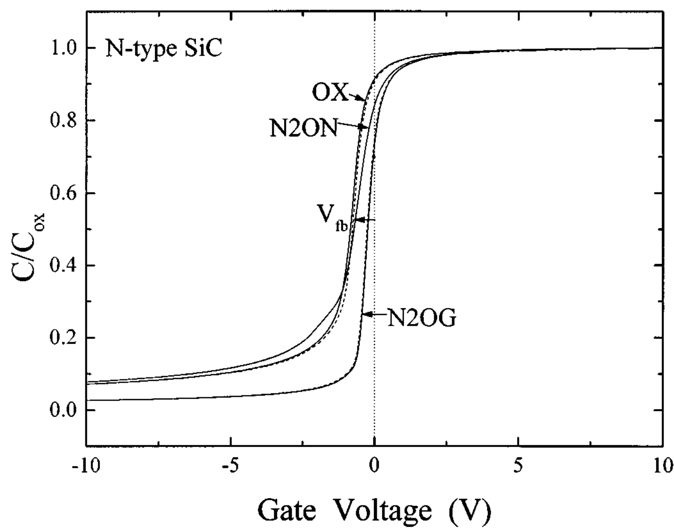
P. T. Lai, C. L. Chan, B. Li, and Y. C. Cheng are with the Department of Electrical and Electronic Engineering, University of Hong Kong, Hong Kong (e-mail: laip@eee.hku.hk).

Publisher Item Identifier S 0741-3106(00)04711-X.

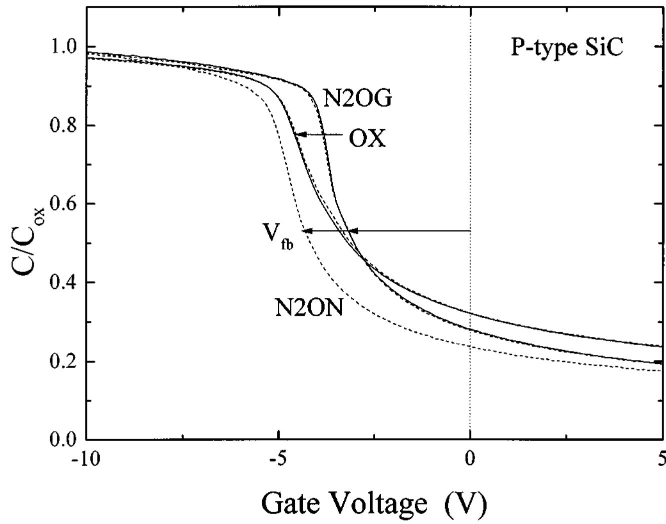
0741–3106/00$10.00 © 2000 IEEE

TABLE I
ELECTRICAL AND PHYSICAL PARAMETERS EXTRACTED FROM HF C–V CURVES

	N-type SiC			P-type SiC		
Sample	N2OG	N2ON	OX	N2OG	N2ON	OX
t_{ox} (Å)	206	217	210	203	213	200
C_{fb}/C_{ox}	0.52	0.53	0.52	0.51	0.53	0.51
V_{fb} (V)	-0.21	-0.65	-0.81	-3.05	-4.31	-3.40
$Q_{ox} \times 10^{11}$ cm^{-2}	2.5	5.9	8.2	5.4	16.7	9.4



(a)



(b)

Fig. 1. High-frequency C–V curve of all capacitors under dark condition, swept in two directions: depletion to accumulation (dashed line) and accumulation to depletion (solid line): (a) n-type sample and (b) p-type sample. Area of capacitor is 1.8×10^4 cm^2.

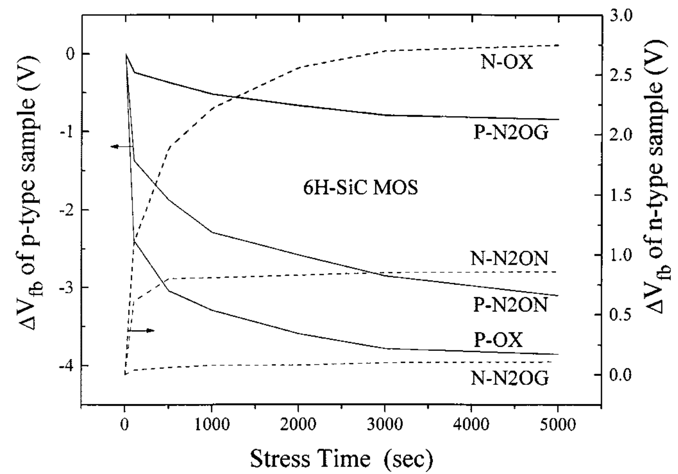


Fig. 2. Flat-band voltage shift of all samples under high-field stressing (±7.0 MV/cm) at room temperature. P-means p-type sample while N-means n-type sample. Area of capacitor is 1.8×10^4 cm^2. Stress field = (gate voltage—V_{fb})/t_{ox}.

with N being acceptor or donor doping density and T the temperature in Kelvin. Oxide-charge density is calculated as $Q_{ox} = -C_{ox}(V_{fb} - \phi_{ms})/q$, where the work-function difference ϕ_{ms} between aluminum and 6H-SiC is calculated to be 0.031 V for n-type SiC and −2.53 V for p-type SiC. Unlike p-type N2ON sample, n-type N2ON sample also presents slightly improved C–V behavior, which is associated with preexisting nitrogen at the SiO_2/SiC interface arising from the nitrogen- doped n-type substrate. Naturally, quality improvement of p-type N2OG sample can be deduced to come from nitrogen incorporation near the interface during N_2O oxidation, which is further confirmed by the stressing results below.

Presented in Fig. 2 are the flat-band voltage shifts of all the samples during a high-field stressing (+7 MV/cm for n-type samples and −7 MV/cm for p-type samples) at room temperature. Negative/positive ΔV_{fb} means generations of donor-type/acceptor-type interface states and positive/negative oxide charges. A much smaller ΔV_{fb} is obtained for both n-type N2OG and p-type N2OG samples, implying significantly suppressed generations of interface states and oxide traps in the two devices. In fact, the 0.1-V shift of the former after 5000 s is also much smaller than 0.4 V of DRY sample (not shown). Moreover, after N_2O nitridation, the shift of DRY sample further increases to 0.8 V, indicating a deterioration

of its interface [3]. From the maximum ΔV_{fb} at 5000-s stress time, increase of effective oxide charge is estimated to be $2.7/4.1 \times 10^{12}$ cm^{-2} for n-/p-OX samples, $7.5/29 \times 10^{11}$ cm^{-2} for n-/p-N2ON samples and $1.1/8.8 \times 10^{11}$ cm^{-2} for n-/p-N2OG samples. The greatly enhanced resistance of N2OG devices against the high-field stress should result from appreciable nitrogen incorporation at/near the SiO_2/SiC interface during oxide growth [8], [9] and thus formation of strong Si–N and O–N bonds [10], just like Si MOSFET's with N_2O-grown oxide as gate dielectric [9]–[12]. The two N2ON samples, especially n-N2ON sample , also exhibit smaller ΔV_{fb} than OX sample (although p-type sample has poor prestress HF *C–V* characteristics), supporting the above suggestion. In addition, during the initial 100-s stress time, ΔV_{fb} should mainly be linked to preexisting donor-/acceptor-type interface states and near-interface hole/electron traps, which are both neutral due to electron/hole occupations before the stress. From this, it can be proposed that N2OG oxide has much fewer donor-/acceptor-type interface states and oxide traps than OX oxide. This is in good agreement with the results in Table I. Therefore, it can be suggested that N_2O-grown oxide on both n- and p-type SiC substrates can lead to not only fewer interface states and oxide charges, but also hardened interface and near-interface oxide due to nitrogen pile-up near the interface.

IV. Summary

N_2O-grown oxide on both n- and p-type 6H–SiC wafers was successfully fabricated for the first time. Improved SiC/SiO_2 interface and oxide qualities were demonstrated in N_2O-grown MOS devices, especially for p-type devices. Moreover, considerably enhanced device reliability under high-field stress was observed with much smaller flat-band voltage shift than N_2O-nitrided and thermal-oxide devices. All these gains are attributed to significant nitrogen incorporation near the SiC/SiO_2 interface during N_2O oxidation. Therefore, N_2O oxidation technique could have great potential in making high-quality and high-reliability SiC MOSFET's, especially n-channel ones.

References

[1] S. T. Sheppard, J. A. Cooper, Jr., and M. R. Melloch, "Non-equilibrium characteristics of the gate-controlled diode in 6H–SiC," *J. Appl. Phys.*, vol. 75, pp. 3205–3207, 1994.

[2] D. Alok, P. K. McLarty, and B. J. Baliga, "Electrical properties of thermal oxide grown using dry oxidation on p-type 6H–silicon carbide," *Appl. Phys. Lett.*, vol. 65, pp. 2177–2178, 1994.

[3] S. Dimitrijev, H. F. Li, H. B. Harrison, and D. Sweatman, "Nitridation of silicon-dioxide films grown on 6H silicon carbide," *IEEE Electron Device Lett.*, vol. 18, pp. 175–177, May 1997.

[4] H. F. Li, S. Dimitrijev, and H. B. Harrison, "Improved reliability of NO-nitrided SiO_2 grown on p-type 4H–SiC," *IEEE Electron Device Lett.*, vol. 19, pp. 279–281, Aug. 1998.

[5] S. M. Tang *et al.*, *J. Electrochem. Soc.*, 1990, vol. 137, p. 221.

[6] S. Zaima, K. Onoda, Y. Koide, and Y. Yasude, *J. Appl. Phys.*, 1990, vol. 68, p. 6304.

[7] D. K. Schroder, *Semiconductor Material and Device Characterization*, 2nd ed. New York: Wiley, 1998.

[8] T. Hori and H. Iwasaki, *J. Appl. Phys.*, 1989, vol. 65, p. 629.

[9] W. Ting, H. Hwang, J. Lee, and D. L. Kwong, "Composition and growth kinetics of ultra-thin SiO_2 films formed by oxidizing Si substrates in N_2O," *Appl. Phys. Lett.*, vol. 57, p. 2808, 1990.

[10] T. Y. Chu *et al.*, "Study of the composition of thin dielectrics grown on Si in a pure N_2O ambient," *Appl. Phys. Lett.*, 1991.

[11] W. Ting *et al.*, "MOS characteristics of ultrathin SiO_2 prepared by oxidizing Si in N_2O," *IEEE Electron Device Lett.*, vol. 12, p. 416, 1991.

[12] G. Q. Lo, W. Ting, J. Ahn, and D. L. Kwong, "Improved performance and reliability of MOSFET's with ultra-thin gate oxides prepared by conventional furnace oxidation of Si in pure N_2O ambient," in *Proc. VLSI Tech. Symp. Dig.*, 1991, p. 43.