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Atomic layer deposition of ZrO_2 as gate dielectrics for AlGaIn/GaN metal-insulator-semiconductor high electron mobility transistors on silicon

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In this Letter, the device performance of AlGaIn/GaN metal-insulator-semiconductor high electron mobility transistors (MISHEMTs) on silicon substrate using 10-nm-thick atomic-layer-deposited ZrO_2 as gate dielectrics is reported. The ZrO_2 AlGaIn/GaN MISHEMTs showed improved maximum drain current density (I_{dmax}) with high peak transconductance (g_{mmax}) as comparison to Schottky-barrier-gate HEMTs (SB-HEMTs). Also compared to SB-HEMTs, reverse gate leakage current was four orders of magnitude lower and forward gate bias extended to +7.4 V. At energy from -0.29 eV to -0.36 eV, low interface trap state density evaluated by AC conductance and “Hi-Lo frequency” methods indicates good quality of atomic-layer-deposited ZrO_2 dielectric layer.

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GaN high electron mobility transistors (HEMTs) have demonstrated their superior performance for high frequency,¹ high power,² and low noise³ applications. However, the high gate leakage current of these HEMTs limits the gate voltage swing and therefore the maximum channel current can be reached.⁴ Utilization of GaN metal-insulator-semiconductor HEMTs (MISHEMTs) with a thin dielectric film as gate insulator is one of the effective solutions to reduce the high gate leakage current with the improvement of device performance.⁵ ZrO_2 , with a high dielectric constant (18–25) (Ref. 6) and large band gap (5.2–7.8 eV),⁷ is a good candidate for the gate insulation layer. ZrO_2 gate dielectric layer, prepared by electron beam evaporation (E-beam)^{6–8} and metal organic chemical vapor deposition (MOCVD)⁹ techniques, was reported at early stage for GaN-based MISHEMTs research. In recent years, due to its capability of depositing ultra-thin films with the benefits of nanometer scalability, high uniformity, good coverage, low defect density, etc., atomic-layer-deposition (ALD) technique is widely utilized for the purpose of research and industrial applications. Thus, introduction of ALD ZrO_2 oxide layer as gate dielectrics is a good option to further increase the device performance of GaN-based MISHEMTs. Abermann *et al.*¹⁰ have reported the influence of *ex-situ* chemical surface cleaning and *in-situ* InAlN surface pre-treatment on current collapse issues for ZrO_2 InAlN/GaN MISHEMTs. On the other hand, Alexewicz *et al.*¹¹ explained the relationship between threshold voltage and ALD ZrO_2 dielectric layer thickness for InAlN/GaN MISHEMTs. However, to-date, comprehensive study was not carried out in AlGaIn/GaN MISHEMTs on Si with ALD ZrO_2 as gate dielectrics. In this Letter, AlGaIn/GaN MISHEMTs on Si using 10-nm-thick ALD ZrO_2 as insulator layer are demonstrated, and the analysis of interface trapping effects are also conducted. For ALD ZrO_2 AlGaIn/GaN MISHEMTs, the reverse gate leakage current was suppressed by about four orders of magnitude and forward gate input bias extended to a high value of +7.4 V. In addition, low interface trap state density in the energy range

from -0.29 eV to -0.36 eV was also evaluated by “Hi-Lo frequency” and AC conductance methods.

The schematic cross-section diagram of MISHEMTs is illustrated in Fig. 1. Device fabrication started from mesa isolation by inductively coupled plasma etching. Then, Ti/Al/Ni/Au was deposited followed by rapid thermal annealing at 825 °C for 30 s in N_2 ambient for ohmic contacts formation. Before gate dielectric deposition, samples were treated by buffered oxide etchant solution to remove the surface native oxide. ZrO_2 gate dielectric layer was deposited by a Cambridge Nanotech Savannah ALD system with tetrakis-(diethylamino)-zirconium and H_2O as precursors. Chamber pressure and substrate temperature were 0.6 Torr and 250 °C, respectively. During the deposition, sequential 400 ms and 40 ms pulse of H_2O and Zr sources were introduced into the chamber separately. After each pulse of gas, the chamber was purged with N_2 for 6 s to remove excess precursor and by-product gases. The dielectric thickness was 10 nm after 120 growth cycles. Subsequently, the Ni/Au gate was formed by lift-off process. Conventional Schottky-barrier-gate HEMTs (SB-HEMTs) were also fabricated with the same layer structure for reference. The devices used for characterizations are with gate length of $L_g = 1.9 \mu\text{m}$, gate width of $W_g = 2 \times 100 \mu\text{m}$, gate-to-source distance of $L_{gs} \sim 0.9 \mu\text{m}$, and gate-to-drain distance of $L_{gd} \sim 1.5 \mu\text{m}$.

Dielectric constant ϵ_{ox} of ALD ZrO_2 was characterized by using a metal-insulator-metal (MIM) structure on the wafer. Values in a range from 17 to 19 was obtained, which is consistent with the values reported in literatures.^{6–9} Fig. 2(a) plots C-V characteristics of SB diodes and ZrO_2 MIS diodes at a high frequency of 1 MHz and Fig. 2(b) shows frequency dispersion between 10 kHz and 1 MHz for C-V curves of ZrO_2 MIS diodes. Sharp transition from accumulation to depletion, small hysteresis voltage shift (illustrated in Fig. 2(a)), and negligible dispersion between 10 kHz and 1 MHz C-V curves for ZrO_2 MIS diodes indicate good quality of ALD ZrO_2 with small amounts of traps inside the oxide and/or at the interface. Thickness of ZrO_2 dielectric layer can also be determined by comparison of SB and MIS diodes

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FIG. 1. Schematic diagram of the AlGaIn/GaN MISHEMTs with 10-nm-thick ALD ZrO₂ as gate dielectrics.

capacitance at zero gate bias (accumulation region) by $1/C_{\text{MIS}} = 1/C_{\text{SB}} + 1/C_{\text{ox}}$. Taken ϵ_{ox} as 18, d_{ox} was assumed to be 9.9 nm, which is in agreement with the designed thickness.

“Hi-Lo frequency” and AC conductance are two commonly used methods to determine the interface state traps (D_{it}).¹² For “Hi-Lo frequency” method, information of trap effects is extracted from the difference between measured capacitance at high frequency 1 MHz (C_{HF}) and low frequency 10 kHz (C_{LF}) by equation $D_{\text{it}} = (C_{\text{LF}} - C_{\text{HF}}) / [q(1 - C_{\text{LF}}/C_{\text{ox}})(1 - C_{\text{HF}}/C_{\text{ox}})]$.¹² AC conductance method is based on analyzing loss caused by the change in trap level charge states through measuring the equivalent parallel conductance G_p as a function of bias voltage and frequency. Assuming a continuum of trap energy levels, D_{it} and time constant τ_{it} can be evaluated by fitting G_p as a function of $\omega = 2\pi f$ according to $G_p/\omega = (qD_{\text{it}}/2\omega\tau_{\text{it}})\ln[1 + (\omega\tau_{\text{it}})^2]$.¹² As illustrated in Fig. 3 (inset), G_p/ω as a function of radial frequency ω at different gate biases are plotted. D_{it} can be determined from $(2.5/q)(G_p/\omega)_{\text{max}}$ and τ_{it} can be evaluated from ω at the peak conductance location on the ω -axis by $\tau_{\text{it}} = 2/\omega$. Extracted D_{it} as a function of trap state energy E_T is shown in Fig. 3. E_T at a certain gate bias can be determined by using the time constant τ_{it} through $E_T = E - E_c = -k_B T \ln(\tau_{\text{it}}\sigma_T N_{\text{CV}})$ (relative parameters can be found in Ref. 13). Due to the limitation of given frequency range (from 10 kHz to 1 MHz) and measurements only conducted at room temperature, E_T is limited in the range of -0.29 eV to -0.36 eV. As shown in Fig. 3, reduction of D_{it} from $4 \times 10^{11} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ and $3 \times 10^{11} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ at -0.29 eV to $7 \times 10^{10} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ and $1 \times 10^{11} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ at -0.36 eV

FIG. 2. (a) Comparison of C - V curves between ZrO₂ MIS diodes and SB diodes measured at frequency of 1 MHz. (b) Frequency dispersion between 10 kHz and 1 MHz for C - V curves of ZrO₂ MIS diodes.

FIG. 3. Extracted D_{it} as a function of energy obtained by “Hi-Lo frequency” and AC conductance methods conducted at room temperature from 10 kHz to 1 MHz for ALD ZrO₂ AlGaIn/GaN MIS diodes. Inset: G_p/ω versus ω of ALD ZrO₂ AlGaIn/GaN MIS diodes at different gate biases. Solid lines are fitting curves.

was observed for AC conductance and “Hi-Lo frequency” methods, respectively. Compared with D_{it} determined by AC conductance method on 10-nm-thick ALD Al₂O₃ AlGaIn/GaN MIS structures reported by Gregušová *et al.*,¹⁴ our result is slightly lower in the similar energy range. This indicates good interface property of the ALD grown ZrO₂ on nitride-based semiconductor surface.

Fig. 4(a) shows $I_{\text{DS}}-V_{\text{DS}}$ characteristics of ALD ZrO₂ AlGaIn/GaN MISHEMTs and Fig. 4(b) compares DC transfer

FIG. 4. (a) $I_{\text{DS}}-V_{\text{DS}}$ characteristics for ALD ZrO₂ AlGaIn/GaN MISHEMTs. (b) Comparison of transfer curves between ALD ZrO₂ AlGaIn/GaN MISHEMTs and referenced AlGaIn/GaN SB-HEMTs.

FIG. 5. Comparison of gate I - V characteristics of ALD ZrO₂ AlGaIn/GaN MISHEMTs and referenced AlGaIn/GaN SB-HEMTs.

TABLE I. Comparison of key parameters of reported ZrO₂ GaN-based MISHEMTs in literatures with those in this work.

T_{ox} (nm)	Deposition method	L_g (μm)	Peak g_m (mS/mm)	Magnitude of reduction for I_g (at $V_g = -10$ V)	Forward V_g (V) (at $I_g = 1$ mA/mm)	E_{ox} (MV/cm)	Ref.
10	E-beam	1	96.74	1 order	3	N.A	7
10.5–11	ALD	2	N.A	3 orders	≥ 2	N.A	10
10	ALD	1	140	N.A	~ 6	N.A	11
10	MOCVD	2	110	4 orders	4	4	9
30	E-beam	2	140	4 orders	N.A	7.15	8
10	ALD	1.9	138	4 orders	7.4	7.4	This work

characteristics for ALD ZrO₂ AlGaIn/GaN MISHEMTs and SB-HEMTs. Obviously, MISHEMTs can operate at a high gate voltage of +5 V with low gate leakage. ZrO₂ MISHEMTs also exhibited higher maximum drain current densities (I_{dmax}) of 790 mA/mm as compared to SB-HEMTs ($I_{\text{dmax}} = 638$ mA/mm). As expected, MISHEMTs showed a shift of threshold voltage ($V_{\text{TMS}} = -3.9$ V) with a slight reduction of the maximum extrinsic transconductance ($g_{\text{mmax}} = 138$ mS/mm) as compared with those for SB-HEMTs ($V_{\text{TSB}} = -3.0$ V and $g_{\text{mmax}} = 146$ mS/mm). The gate-to-channel modulation ability was slightly reduced due to the insertion of ZrO₂ insulator, which results in the shift of threshold voltage and smaller g_{mmax} .⁷ I_G - V_G characteristics for ZrO₂ MISHEMTs and SB-HEMTs are shown in Fig. 5. Compared with SB-HEMTs, reverse gate leakage was reduced by about four orders of magnitude for MISHEMTs. More importantly, a forward gate bias voltage as high as +7.4 V can be reached if the limit of gate leakage is defined at 1 mA/mm. This gives the oxide electrical strength of ~ 7.4 MV/cm, which is the highest value achieved by ZrO₂ on GaN-based MISHEMTs reported so far. The high forward gate bias voltage allows for higher input voltage swing to be applied at the gate. Table I compares the key parameters of GaN-based MISHEMTs using ZrO₂ as gate dielectrics in literatures with those measured results from our devices. It can be seen from this table that the introduction of 10-nm-thick ALD ZrO₂ insulating layer has the advantage to both reduction of gate leakage current and increment of forward input gate voltage to +7.4 V while still maintaining a reasonable g_{mmax} value.

In conclusion, AlGaIn/GaN MISHEMTs on high resistivity Si substrate using 10-nm-thick ALD ZrO₂ as gate dielectrics are demonstrated. Devices with $L_g = 1.9$ μm showed g_{mmax} of 138 mS/mm and I_{dmax} of 790 mA/mm. Compared with SB-HEMTs, ALD ZrO₂ AlGaIn/GaN MISHEMTs showed a reduction of reverse gate leakage by four orders of magnitude and significant improvement of gate forward bias voltage (+7.4 V). Low interface trap

density (D_{it}) in range of $7 \times 10^{10} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ to $4 \times 10^{11} \text{ cm}^{-2} \cdot \text{eV}^{-1}$ obtained by using AC conductance and “Hi-Lo frequency” methods suggests good interface quality between ALD ZrO₂ and nitride-based semiconductor surface. These results indicate great potential for the usage of ALD ZrO₂ AlGaIn/GaN MISHEMTs for high frequency and high power applications.

- ¹V. Kumar, W. Lu, R. Schwindt, A. Kuliev, G. Simin, J. Yang, M. A. Kahn, and I. Adesida, *IEEE Electron Device Lett.* **23**, 455 (2002).
- ²T. Palacios, A. Chakraborty, S. Rajan, C. Poblenz, S. Keller, S. P. DenBaars, J. S. Speck, and U. K. Mishra, *IEEE Electron Device Lett.* **26**, 781 (2005).
- ³I. Adesida, W. Lu, and V. Kumar, in *Proceeding of 6th International Conference on Solid-State and Integrated Circuit Technology*, Shanghai, China, 22–25 October (Institute of Electrical and Electronics Engineers, Inc. and People's Posts & Telecommunications Publishing House, Beijing, 2001), Vol. 2, pp. 1163–1168.
- ⁴T. Hashizume, S. Ootomo, and H. Hasegawa, *Appl. Phys. Lett.* **83**, 2952 (2003).
- ⁵Z. H. Liu, G. I. Ng, S. Arulkumaran, Y. K. T. Maung, K. L. Teo, S. C. Foo, V. Sahnuganathan, T. Xu, and C. H. Lee, *IEEE Electron Device Lett.* **31**, 803 (2010).
- ⁶S. Rai, V. Adivarahan, N. Tipimani, A. Koudymov, J. Yang, G. Simin, and M. A. Khan, *Jpn. J. Appl. Phys., Part 1* **45**, 4985 (2006).
- ⁷C.-H. Chen, H.-C. Chiu, F.-T. Chien, H.-W. Chuang, K.-J. Chang, and Y.-T. Gau, *Microelectron. Reliab.* **52**, 2551 (2012).
- ⁸K. Balachander, S. Arulkumaran, H. Ishikawa, K. Baskar, and T. Egawa, *Phys. Status Solidi A* **202**, R16 (2005).
- ⁹J. Kuzmik, G. Pozzovivo, S. Abermann, J. F. Carlin, M. Gonschorek, E. Feltn, N. Grandjean, E. Bertagnolli, G. Strasser, and D. Pogany, *IEEE Trans. Electron Devices* **55**, 937 (2008).
- ¹⁰S. Abermann, G. Pozzovivo, J. Kuzmik, C. Ostermaier, C. Henkel, O. Bethge, G. Strasser, D. Pogany, J. F. Carlin, N. Grandjean, and E. Bertagnolli, *IEEE Electron. Lett.* **45**, 570 (2009).
- ¹¹A. Alexewicz, C. Ostermaier, C. Henkel, O. Bethge, J.-F. Carlin, L. Lugani, N. Grandjean, E. Bertagnolli, D. Pogany, and G. Strasser, *Thin Solid Films* **520**, 6230 (2012).
- ¹²D. K. Schroder, *Semiconductor Material and Device Characterization*, 3rd ed. (Wiley, Hoboken, NJ, 2006), pp. 319–387.
- ¹³P. Kordoš, R. Stoklas, D. Gregušová, and J. Novák, *Appl. Phys. Lett.* **94**, 223512 (2009).
- ¹⁴D. Gregušová, R. Stoklas, Ch. Mizue, Y. Hori, J. Novák, T. Hashizume, and P. Kordoš, *J. Appl. Phys.* **107**, 106104-1 (2010).