Frequency-Dependent Capacitance Reduction in High-k $AlTiO_x$ and Al_2O_3 Gate Dielectrics From IF to RF Frequency Range

S. B. Chen, C. H. Lai, K. T. Chan, Albert Chin, *Senior Member, IEEE*, J. C. Hsieh, and J. Liu

***Abstract*—We have characterized the capacitance and loss tangent for high-k Al_2O_3 and $AlTiO_x$ gate dielectrics from IF (100 KHz) to RF (20 GHz) frequency range. Nearly the same rate of capacitance reduction as SiO_2 was demonstrated individually by the proposed Al_2O_3 and $AlTiO_x$ gate dielectrics as frequency was increased. Moreover, both dielectrics preserve the higher k better than SiO_2 from 100 KHz to 20 GHz. These results suggest that both Al_2O_3 and $AlTiO_x$ are suitable for next generation MOSFET application into RF frequency regime.**

***Index Terms*—Dielectric constant, frequency dependence, high k, loss tangent, RF.**

I. Introduction

IN SPITE of the fast progress of conforming to high-k gate dielectrics [1]–[4], very few literatures have reported RF performance employing high-k gate dielectrics so far. However, the current operation speed of microprocessor is already >1 GHz. Among various characteristics due to RF performance, the frequency-dependent dielectric constant at RF regime is one of the most important factors because preserving its high-k nature at high frequencies is a fundamental requirement and a major advantage compared with SiO_2. In reality, the frequency-dependent capacitance reduction of high-k Si_3N_4 has been reported. Still, the operation frequency is not high enough to assure high-k dielectrics to be used for RF application [5]. In this paper, we have investigated the frequency-dependent capacitance reduction of Al_2O_3 and $AlTiO_x$ ranging from Intermediate Frequency (IF) (100 KHz) to RF (20 GHz). It was revealed that Al_2O_3 and $AlTiO_x$ gate dielectrics displayed nearly the same degradation rate of capacitance reduction as SiO_2 with the increment of frequency, and preserved higher k quality better than SiO_2 over the entire measurement frequencies. These results proved that the proposed application of high-k Al_2O_3 and $AlTiO_x$ into RF regime was a successful one.

Manuscript received November 26, 2001; December 27, 2001. This work was supported by NSC Grant 90-2215-E-009-052 and UMC. The review of this letter was arranged by Editor K. De Meyer.

S. B. Chen, J. H. Chou, K. T. Chang, and A. Chin are with the Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: achin@cc.nctu.edu.tw).

J. C. Hsieh and J. Liu are with United Microelectronic Corporation, Hsinchu, Taiwan, R.O.C.

Publisher Item Identifier S 0741-3106(02)03204-4.

II. Experimental

The MOS capacitors were fabricated using a 4-in p-type Si wafer with its resistivity value ranging from 5–10 Ω-cm. Wafers were passivated by HF vapor first, and then deposited with Al or Ti/Al bi-layer (thickness of bilayer $\sim 1:1$) separately in a high vacuum chamber [9]. By directly oxidizing Al or Ti/Al bi-layer wafers in a furnace, then followed by high temperature annealing, high-k Al_2O_3 or $AlTiO_x$ film was obtained, respectively, [4]. In consideration of RF characterization, high-k Al_2O_3 and $AlTiO_x$ dielectrics with coplanar transmission lines [6]–[8] were fabricated on Si where the lower transmission line was patterned by n^+ Si. The motivation of utilizing $AlTiO_x$ is to increase k and to achieve low equivalent-oxide thickness (EOT). In addition, it also preserves the merit of slow oxygen diffusion through Al–O matrix to achieve the low EOT, similar to Si_3N_4. Finally, Al is used for both top capacitor electrode and transmission line with the device area being 20 μm × 20 μm. The Al_2O_3 and $AlTiO_x$ capacitors were measured using an HP4284A precision LCR meter at 100 KHz to 1 MHz, while the S-parameters were measured by an HP8510C network analyzer at 200 MHz to 20 GHz. The reason why S-parameters are used is due to the fact that the usage of Y- or Z-parameters cannot provide us alternatives in measuring complete shorts or opens at high frequencies [10]. Therefore, S-parameters measured from the RF equipments are presented in the Smith chart, which is also a general representation of S-parameters, as reported in [6]–[8], [11].

III. Results and Discussion

We have first measured the low-frequency capacitance. Fig. 1 depicts the C–V characteristics of capacitors with different dielectrics at frequency of 100 KHz and 1 MHz. The flat capacitance–voltage (C–V) characteristics with small capacitance change are caused by the highly doped n^+ Si transmission line. Meanwhile, the EOT values are calculated to be 12.5 and 17.2 Å for $AlTiO_x$ and Al_2O_3 without considering quantum correction factors from $k\varepsilon_0$ A/C, by means of which it can be reused to obtain k values as 15 and 9 for $AlTiO_x$ and Al_2O_3, respectively. Therefore, the approach of utilizing either Al_2O_3 or $AlTiO_x$ as gate dielectric can effectively increase the k value and decrease the EOT. It can be seen that no obvious reduction of capacitance in either dielectric is observed for frequencies ranging from 100 KHz to 1 MHz, indicating that the qualities of $AlTiO_x$ and Al_2O_3 are excellent.

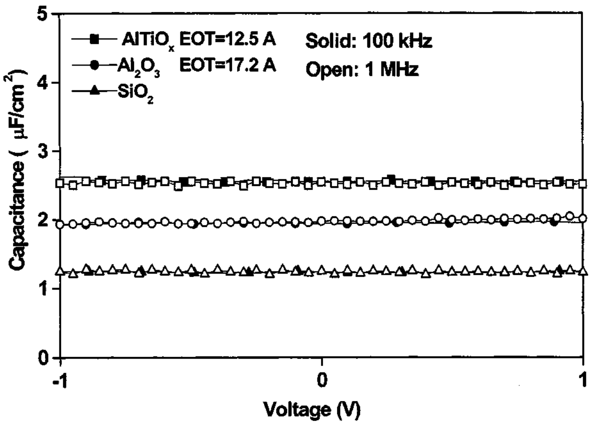


Fig. 1. C–V characteristics of the Al_2O_3 and $AlTiO_x$ capacitors measured at 100 KHz and 1 MHz. Conventional 23 Å SiO_2 is also added for comparison. The measured area is 20 μm × 20 μm.

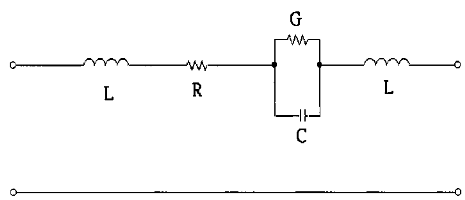
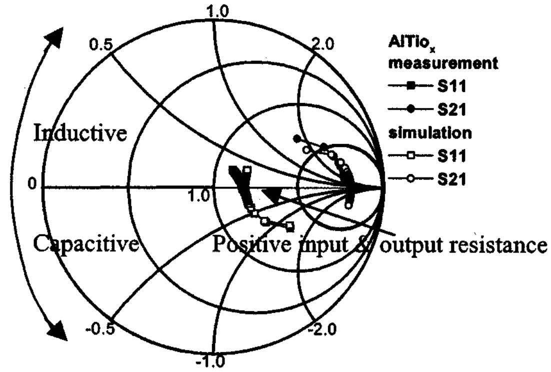


Fig. 2. Equivalent circuit model for capacitor simulation at RF regime.

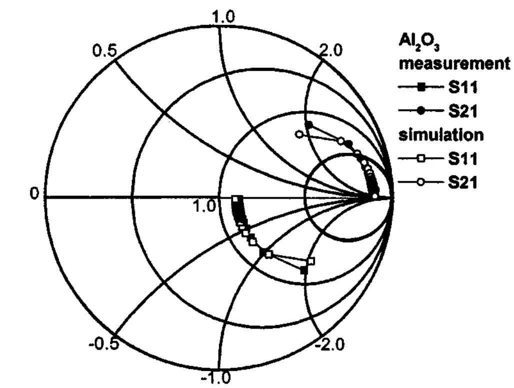
To further determine the capacitance at RF frequency, we have first established the equivalent circuit model for capacitance extraction. As shown in Fig. 2, the shunt C and G are the basic equivalent models for high-k capacitor and small series R and L represent the parasitic resistance and inductance in the coplanar transmission line. Notice that the shunt G is originated from the gate dielectric leakage current. In other words, the gate dielectric having higher leakage current will produce larger loss tangent and power dissipation.

Fig. 3(a)–(c) illustrate the measured and simulated S-parameters of $AlTiO_x$, Al_2O_3, and SiO_2 capacitors, respectively. A good match between measured and simulated data over the wide frequency range suggests that the equivalent circuit model in Fig. 2 is suitable and reliable for capacitor extraction. Notably, as the frequency is increased, the property of circuit could change from capacitive to inductive resulting from the formation of parasitic inductance. For this reason, we have also used Nyquist diagram [12] to study the stability issues for gate capacitors. Deep sub-μm (0.18 μm) MOSFET with gate width of 400 μm was fabricated and analyzed using the Nyquist diagram to demonstrate that these devices are unconditionally stable in passive capacitor at all frequencies due to the following three main reasons: no gain (not an amplifier) [13], no negative resistance [14], and input and output resistance > 0 [15].

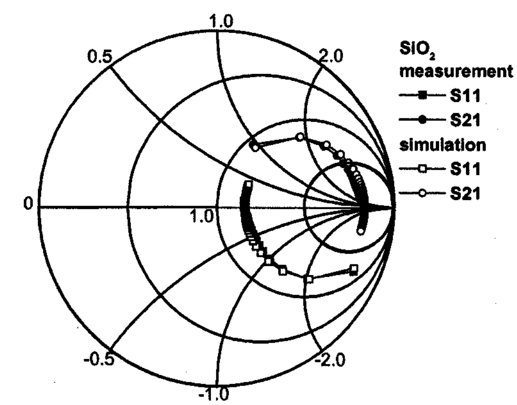
Fig. 4(a) and (b) demonstrate the frequency-dependent capacitance reduction and the loss tangent for various gate dielectrics, respectively. Comparable capacitance reduction of high-k $AlTiO_x$ and Al_2O_3 with SiO_2 can be obtained, suggesting that $AlTiO_x$ and Al_2O_3 are two appropriate candidates to replace SiO_2 to be the next generation gate dielectrics. The



(a)



(b)



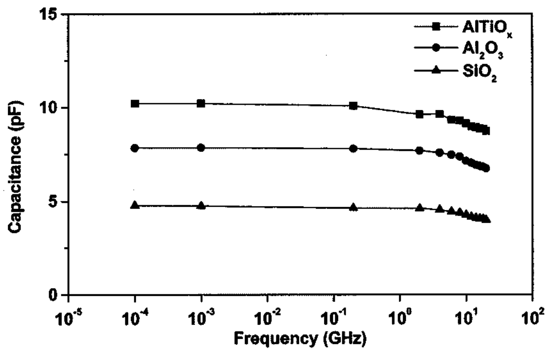
(c)

Fig. 3. Measured and simulated scattering parameters of (a) $AlTiO_x$, (b) Al_2O_3, and (c) SiO_2 capacitors.

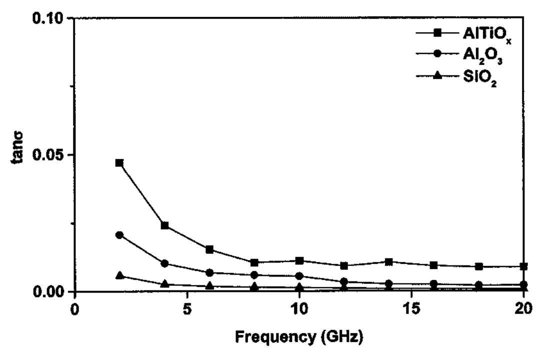
high RF performance can also be evidenced from the very low loss tangent even at a large gate electrode area of 400 μm^2. Although the loss tangent increases with decreasing EOT from SiO_2 to $AlTiO_x$, those values of loss tangent are still low enough to be used for RF application [16].

IV. Conclusion

We have characterized the capacitance and loss tangent of high-k $AlTiO_x$ and Al_2O_3 gate dielectrics up to 20 GHz. Meanwhile, a comparable reduction of capacitance is also obtained from our proposed dielectric films (high-k $AlTiO_x$ and Al_2O_3) at high frequencies, similar to SiO_2. In summary, these two



(a)



(b)

Fig. 4. (a) Frequency-dependent capacitance and (b) loss tangent for $AlTiO_x$, Al_2O_3, and SiO_2 gate dielectrics.

high-k materials are proven to be useful for deep sub-μm RF MOSFET applications at frequencies from IF to RF.

REFERENCES

[1] S. J. Lee, H. F. Luan, C. H. Lee, T. S. Jeon, W. P. Bai, Y. Senzaki, D. Roberts, and D. L. Kwong, "Performance and reliability of ultra thin CVD HfO_2 gate dielectrics with dual poly-Si gate electrodes," in *Proc. Symp. VLSI Technology*, 2001, pp. 133–134.

[2] L. Kang, Y. Jeon, K. Onishi, B. H. Lee, W.-J. Qi, R. Nieh, S. Gopalan, and J. C. Lee, "Single-layer thin HfO_2 gate dielectric with n^+-polysilicon gate," in *Proc. Symp. VLSI Technology*, 2000, pp. 44–45.

[3] X. Guo, X. Wang, Z. Luo, T. P. Ma, and T. Tamagawa, "High quality ultra-thin (1.5 nm) TiO_2–Si_3N_4 gate dielectric for deep sub-micron CMOS technology," in *IEDM Tech. Dig.*, 1999, pp. 137–140.

[4] A. Chin, C. C. Liao, C. H. Lu, W. J. Chen, and C. Tsai, "Device and reliability of high-K Al_2O_3 gate dielectric with good mobility and low D_{it}," in *Proc. Symp. VLSI Technology*, 1999, pp. 133–134.

[5] J. A. Babcock, S. G. Balster, A. Pinto, C. Dirnecker, P. Steinmann, R. Jumpertz, and B. El-Kareh, "Analog characteristics of metal–insulator–metal capacitors using PECVD nitride dielectrics," *IEEE Electron Device Lett.*, vol. 22, pp. 230–232, May 2001.

[6] K. T. Chan, A. Chin, C. M. Kwei, D. T. Shien, and W. J. Lin, "Transmission line noise from standard and proton-implanted Si," in *MTT-S Dig.*, Phoenix, AZ, 2001.

[7] Y. H. Wu, A. Chin, K. H. Shih, C. C. Wu, C. P. Liao, S. C. Pai, and C. C. Chi, "RF loss and crosstalk on extremely high resistivity (10k-1MΩ-cm) Si fabricated by ion implantation," in *MTT-S Dig.*, Boston, MA, 2000, pp. 221–224.

[8] Y. H. Wu, A. Chin, C. S. Liang, and C. C. Wu, "The performance limiting factors as RF MOSFET's scale down," in *Proc. Radio Frequency Integrated Circuits Symp.*, Boston, MA, 2000, pp. 151–155.

[9] A. Chin, W. J. Chen, T. Chang, R. H. Kao, B. C. Lin, C. Tsai, and J. C.-M. Huang, "Thin oxides with *in-situ* native oxide removal," *IEEE Electron Device Lett.*, vol. 18, pp. 417–419, Sept. 1997.

[10] T. H. Lee, *The Design of CMOS RF ICs*. New York: Cambridge Univ. Press, 1998, p. 139.

[11] K. T. Chan, A. Chin, Y. B. Chen, Y.-D. Lin, D. T. S. Duh, and W. J. Lin, "Integrated antennas on Si, proton-implanted Si and Si-on-quartz," in *IEDM Tech. Dig.*, Washington, DC, Dec. 2001.

[12] P. R. Gray, P. J. Hurst, S. H. Lewis, and R. G. Meyer, *Analysis and Design of Analog Integrated Circuits*. New York: Wiley, 2001, p. 628.

[13] A. S. Sedra and K. C. Smith, *Microelectronics Circuits*. Philadelphia, PA: Saunders College, 1989, p. 599.

[14] G. Gonzalez, *Microwave Transistor Amplifiers Analysis and Design*. Englewood Cliffs, NJ: Prentice-Hall, 1997, p. 217.

[15] S. Y. Liao, *Microwave Circuit Analysis and Amplifiers Design*. Englewood Cliffs, NJ: Prentice-Hall, 1987, p. 96.

[16] C.-M. Hung, Y.-C. Ho, I.-C. Wu, and K. O, "High-Q capacitors implemented in a CMOS process for low-power wireless applications," in *MTT-S Dig.*, Baltimore, MD, 1998, pp. 505–511.