Very High Density RF MIM Capacitors (17 $fF/\mu m^2$) Using High-κ Al_2O_3 Doped Ta_2O_5 Dielectrics

M. Y. Yang, C. H. Huang, Albert Chin, *Senior Member, IEEE*, Chunxiang Zhu, B. J. Cho, *Senior Member, IEEE*, M. F. Li, *Senior Member, IEEE*, and Dim-Lee Kwong

***Abstract*—Using high-κ Al_2O_3 doped Ta_2O_5 dielectric, we have obtained record high MIM capacitance density of 17 $fF/\mu m^2$ at 100 KHz, small 5% capacitance reduction to RF frequency range, and low leakage current density of 8.9×10^{-7} A/cm^2. In combination of both high capacitor density and low leakage current density, a very low leakage current of 5.2×10^{-12} A is calculated for a typical large 10 pF capacitor used in RF IC that is even smaller than that of a deep sub-μm MOSFET. This very high capacitance density with good MIM capacitor characteristics can significantly reduce the chip size of RF ICs.**

***Index Terms*—Capacitor, dielectric constant, frequency dependence, high κ, MIM, RF.**

I. Introduction

The MIM capacitors [1]–[6] are widely used in RF circuit for impedance matching and DC filtering which usually consume a large portion of whole RF IC area. To reduce the chip size and cost, the capacitance density must be increased. To achieve higher capacitance density of $\varepsilon_0\kappa/t_d$ in MIM capacitor, the application of high dielectric constant (κ) material [7]–[13] is the ideal choice because the reducing dielectric thickness (t_d) will increase the undesired leakage current. In addition, the proper high-κ dielectric requires not only higher-κ but also process compatible to existing VLSI backend technology. Thus, high quality dielectric must be formed at a very low temperature of 400 °C limited by backend process [11]. Previously, we have reported that high performance RF MIM capacitor can be achieved using high-κ Al_2O_3 dielectric with relatively high capacitance density of 5 $fF/\mu m^2$ [13]. In this letter, we have further increased the capacitance density to 17 $fF/\mu m^2$ using high-κ Al_2O_3 doped Ta_2O_5. Low leakage current density of 8.9×10^{-7} A/cm^2 is also obtained. This excellent result suggests the developed high-κ MIM capacitor can be used for RF circuit with largely reduced device size.

Manuscript received February 10, 2003; revised June 17, 2003. This work was supported by the NSTB/EMT/TP/00/001.2. The review of this letter was arranged by Associate Editor Dr. Arvind Sharma.

M. Y. Yang, C. H. Huang, and A. Chin are with the Department of Electronics Engineering, National Chiao Tung Univ., Hsinchu 300, Taiwan, R.O.C. (e-mail: achin@cc.nctu.edu.tw).

C. Zhu, B. J. Cho, and M. F. Li are with the Silicon Nano Device Laboratory, Department of Electrical and Computer Engineering, National University of Singapore, Singapore, 119260.

D.-L. Kwong is with the Department of Electrical & Computer Engineering, The University of Texas, Austin, TX 78752 USA.

Digital Object Identifier 10.1109/LMWC.2003.818532

II. Experimental

For VLSI integration, we have first deposited 500 nm PECVD SiO_2 on Si substrates. Then bottom electrode and RF transmission line are formed using Pt/Ti bi-layer metal. A second PECVD oxide was deposited for isolation and followed by patterning the active capacitor area. Thin Al:Ta (1:8) layer was deposited on bottom electrode, and oxidized at 400 °C for 45 min to form high-κ Al_2O_3 doped Ta_2O_5. The formed high-κ dielectric was further annealed at 400 °C for 15 min to improve the quality. Two dielectric thicknesses of 11.5 and 14 nm are formed and confirmed by ellipsometer measurement. The reason for doping Al_2O_3 into Ta_2O_5 is to preserve the merit of good MIM capacitor integrity by adding Al_2O_3 dielectric [10]–[13]. Finally, Al metal was used for both top capacitor electrode and transmission line and the formed MIM capacitor area is $50\ \mu m \times 50\ \mu m$. The MIM capacitors were characterized by HP4284A precision LCR meter from 10 KHz to 1 MHz and S-parameters measurement using HP8510C network analyzer from 200 MHz to 20 GHz. The parasitic pad, series inductor and resistor in transmission line are de-embedded from a same line length through transmission line [14], [16].

III. Results and Discussion

We have first measured the low frequency characteristics of high-κ Al_2O_3 doped Ta_2O_5 MIM capacitors. As shown in Fig. 1, record high capacitance density of 17 $fF/\mu m^2$ at 100 KHz is measured for 11.5 nm Al_2O_3 doped Ta_2O_5 device and a κ value of 22 is obtained. The equivalent-oxide thickness (EOT) values for these high density capacitors are calculated to be 2.0 and 2.4 nm for respective 11.5 and 14 nm physical dielectric thickness using $\kappa_{SiO2}\varepsilon_o A/C$, where κ_{SiO2} is the SiO_2 dielectric constant. Such small EOT of 2.0 nm without quantum correction is even suitable for high-κ gate dielectric usage.

Fig. 2 shows the *J–V* characteristics of Al_2O_3 doped Ta_2O_5 MIM capacitors. The asymmetrical *J–V* and breakdown voltages under positive and negative bias are due to the different work function of top Al and bottom Pt electrodes. The leakage current is increased by trading off the increasing capacitance density, and values of 4.5×10^{-7} and 8.9×10^{-7} A/cm^2 are measured at -2 V for respective EOT of 2.4 and 2.0 nm. For a typical large capacitor of 10 pF used in RF ICs, a leakage current of only 5.2×10^{-12} A is calculated that is even smaller than the off-state current of a deep sub-μm MOSFET [17]. Therefore, the leakage current density is low enough for RF IC application. We have also added the stress effect in the inserted figure.

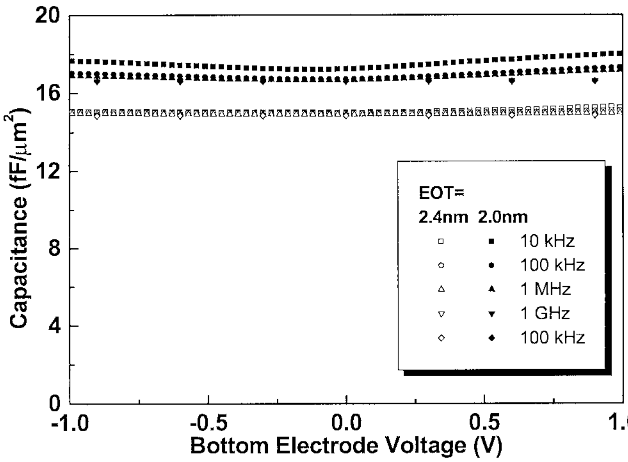

Fig. 1. *C–V* characteristics of (a) 2.0 and (b) 2.4 nm EOT Al_2O_3 doped Ta_2O_5 MIM capacitors at different frequencies. The measured area is $50\ \mu m \times 50\ \mu m$.

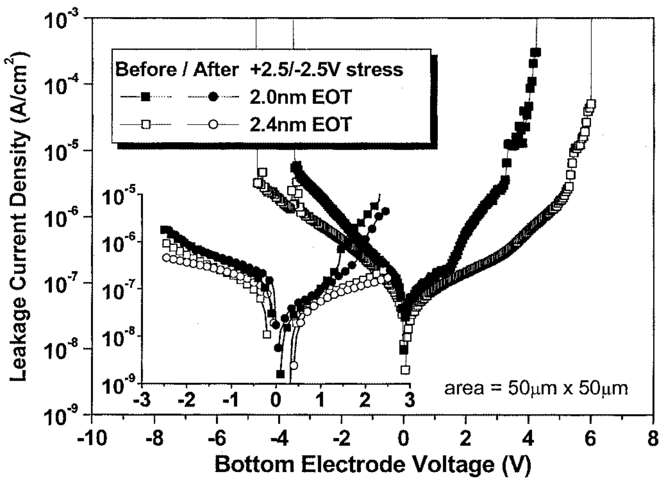

Fig. 2. *J–V* characteristics of 2.0 and 2.4 nm EOT doped Ta_2O_5 MIM capacitors. The insert figure is the stress induced leakage current under ±2.5 V stress for 1000 s. The asymmetric *J–V* and breakdown voltages are due to the different bottom Pt and top Al electrodes.

The good dielectric reliability can be evidenced from the small increase of leakage current under a stress condition of ±2.5 V for 1000 s.

To further study the RF frequency characteristics, we have measured the S-parameters up to 20 GHz. Fig. 3(a) shows the measured (de-embedded) and modeled S-parameters for Al_2O_3 doped Ta_2O_5 MIM capacitors, where the modeled data is from the equivalent circuit model shown in Fig. 3(b). The R_S, L_S, R_P, and C in the model are the parasitic series resistor, series inductor, parallel resistor, and capacitor, respectively. Good agreement between measured and modeled data is obtained for both capacitors with different thickness, which can be used for capacitance extraction.

Fig. 4 shows the frequency-dependent capacitance reduction and quality (Q) factor for high-κ Al_2O_3 doped Ta_2O_5 MIM capacitors. The Q-factors are directly from the measured $1/\tan\delta$ for frequency below 1 MHz and calculated from S-parameters at RF frequencies. The capacitance values at RF frequencies are extracted from the circuit model where well matched data

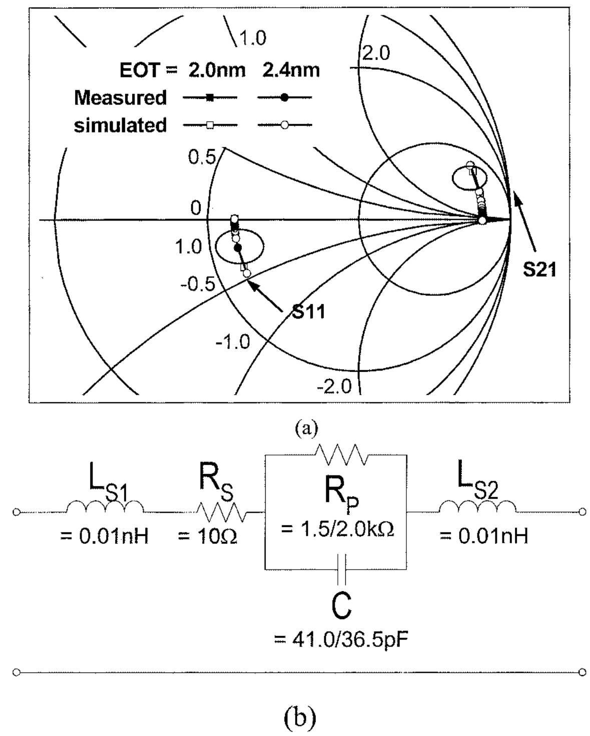

Fig. 3. (a) Measured and simulated scattering parameters of 2.0 and 2.4 nm EOT Al_2O_3 doped Ta_2O_5 MIM capacitors and (b) equivalent circuit model and numerical values of elements for capacitor simulation at RF regime.

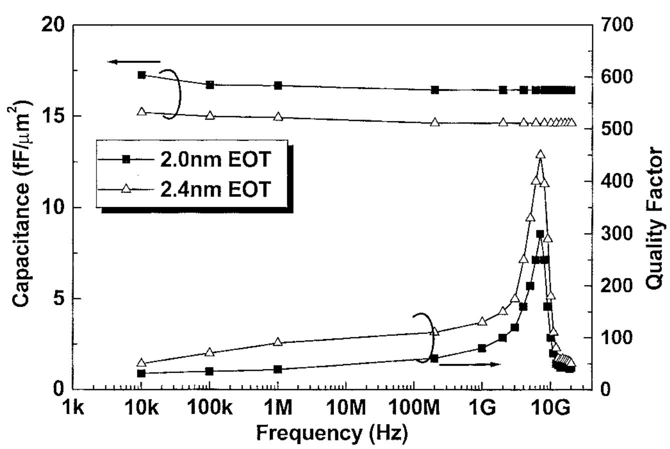

Fig. 4. Frequency-dependent capacitance and Q-factor of 2.0 and 2.4 nm EOT Al_2O_3 doped Ta_2O_5 MIM capacitors.

of modeled and measured S-parameters are shown in Fig. 3. Only a small amount of capacitance reduction (5%) is obtained from 10 KHz to 20 GHz that indicates the excellent performance for RF application. The Q-factor decreases as increasing capacitance density that is due to the higher resistor loss and consistent with the larger leakage current trend. However, an average Q-factor of ~40 is obtained for 17 $fF/\mu m^2$ capacitor that also suggests the good RF performance. A resonant frequency of ~8 GHz is observed due to the very large capacitor (42.5 pF) and residual inductance even after de-embedding. The high capacitor density, low leakage current, small frequency dependence and good Q-factor of Al_2O_3 doped Ta_2O_5 MIM capacitors are useful for circuit application at RF frequencies.

IV. Conclusion

We have achieved record high 17 $\mathrm{fF}/\mu\mathrm{m}^2$ capacitance density, small 5% capacitance reduction to RF frequency range, and low leakage current of $8.9 \times 10^{-7}\ \mathrm{A/cm^2}$ using high-κ $\mathrm{Al_2O_3}$ doped $\mathrm{Ta_2O_5}$ MIM capacitors and processed at 400 $^\circ\mathrm{C}$. This high capacitance density with good device integrity can greatly reduce the chip size of RF ICs.

References

[1] J.-H. Lee, D.-H. Kim, Y.-S. Park, M.-K. Sohn, and K.-S. Seo, "DC and RF characteristics of advanced MIM capacitors for MMIC's using ultra-thin remote-PECVD $\mathrm{Si_3N_4}$ dielectric layers," *IEEE Microwave Guided Wave Lett.*, vol. 9, pp. 345–347, Sept. 1999.

[2] Z. Chen, L. Guo, M. Yu, and Y. Zhang, "A study of MIMIM on-chip capacitor using $\mathrm{Cu/SiO_2}$ interconnect technology," *IEEE Microwave Wireless Components Lett.*, vol. 12, pp. 246–248, July 2002.

[3] C. P. Yue and S. S. Wong, "A study on substrate effects of silicon-based RF passive components," in *IEEE MTT-S Dig.*, 1999, pp. 1625–1628.

[4] 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 *IEEE MTT-S Int. Microwave Symp.*, 1998, pp. 505–511.

[5] K. Shao, S. Chu, K.-W. Chew, G.-P. Wu, C.-H. Ng, N. Tan, B. Shen, A. Yin, and Z.-Y. Zheng, "A scaleable metal-insulator-metal capacitors process for 0.35 to 0.18 $\mu\mathrm{m}$ analog and RFCMOS," in *Proc. 6th Int. Conf. on Solid-State and Integrated-Circuit Technol., 2001*, 2001, pp. 243–246.

[6] S. V. Huylenbroeck, S. Decoutere, R. Jenei, and G. Winderickx, "Investigation of PECVD dielectrics for nondispersive metal-insulator-metal capacitors," *IEEE Electron Device Lett.*, vol. 23, pp. 191–193, 2002.

[7] 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 $\mathrm{HfO_2}$ gate dielectrics with dual poly-Si gate electrodes," in *Proc. Symp. VLSI Technology*, 2001, pp. 133–134.

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

[9] M. Y. Yang, S. B. Chen, A. Chin, C. L. Sun, B. C. Lan, and S. Y. Chen, "One-transistor $\mathrm{PZT/Al_2O_3}$, $\mathrm{SBT/Al_2O_3}$ and $\mathrm{BLT/Al_2O_3}$ stacked gate memory," in *IEDM Tech. Dig.*, 2001, pp. 795–798.

[10] H. Hu, C. Zhu, X. F. Yu, A. Chin, M. F. Li, B. J. Cho, D.-L. Kwong, M. B. Yu, and P. D. Foo, "MIM capacitors using atomic-layer-deposited high-k $\mathrm{(HfO_2)_{1-x}(Al_2O_3)_x}$ dielectrics," *IEEE Electron Device Lett.*, vol. 24, pp. 60–62, Feb. 2003.

[11] S. B. Chen, J. H. Chou, A. Chin, J. C. Hsieh, and J. Liu, "High density MIM capacitors using $\mathrm{Al_2O_3}$ and $\mathrm{AlTiO_x}$ dielectrics," *IEEE Electron Device Lett.*, vol. 23, pp. 185–187, Apr. 2002.

[12] S. B. Chen, J. H. Chou, K. T. Chan, A. Chin, J. C. Hsieh, and J. Liu, "Frequency-dependent capacitance reduction in high-k $\mathrm{AlTiO_x}$ and $\mathrm{Al_2O_3}$ gate dielectrics from IF to RF frequency range," *IEEE Electron Device Lett.*, vol. 23, pp. 203–205, Apr. 2002.

[13] S. B. Chen, J. H. Chou, A. Chin, J. C. Hsieh, and J. Liu, "RF MIM capacitors using high-K $\mathrm{Al_2O_3}$ and $\mathrm{AlTiO_x}$ dielectrics," in *Proc. IEEE MTT-S Int. Microwave Symp.*, vol. 1, June 2002, pp. 201–204.

[14] 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 *Proc. IEEE MTT-S Int. Microwave Symp.*, June 2001, pp. 763–766.

[15] 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.*, 2001, pp. 903–906.

[16] 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 (10 k-1 MΩ-cm) Si fabricated by ion implantation," in *Proc. IEEE MTT-S Int. Microwave Symp.*, 2000, pp. 221–224.

[17] 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.*, 2000, pp. 151–155.