High-Performance MIM Capacitor Using ALD High-κ HfO_2–Al_2O_3 Laminate Dielectrics

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***Abstract*—For the first time, we successfully fabricated and demonstrated high performance metal–insulator–metal (MIM) capacitors with HfO_2–Al_2O_3 laminate dielectric using atomic layer deposition (ALD) technique. Our data indicates that the laminate MIM capacitor can provide high capacitance density of 12.8 $fF/\mu m^2$ from 10 kHz up to 20 GHz, very low leakage current of 3.2×10^{-8} A/cm^2 at 3.3 V, small linear voltage coefficient of capacitance of 240 ppm/V together with quadratic one of 1830 ppm/V^2, temperature coefficient of capacitance of 182 $ppm/^\circ C$, and high breakdown field of $\sim$6 MV/cm as well as promising reliability. As a result, the HfO_2–Al_2O_3 laminate is a very promising candidate for next generation MIM capacitor for radio frequency and mixed signal integrated circuit applications.**

***Index Terms*—Atomic layer deposition (ALD), HfO_2–Al_2O_3 laminate, high-κ, metal–insulator–metal (MIM) capacitor.**

I. INTRODUCTION

THE trend in the on-chip integrated passive devices for wireless applications triggers the demand for metal–insulator–metal (MIM) capacitors embedded into the interlevel dielectric layers to enhance radio frequency (RF) performance. With an increase in levels of integration and scale–down of chip size, integrated RF capacitors with higher capacitance density will be required in future technology. High capacitance density can be achieved by employing either high-κ materials or very thin dielectric films. However, leakage current and reliability issues limit the thickness scaling [1]. Therefore, high-κ materials are much preferred as a possible solution. Recently, various potential high-κ dielectrics have been investigated for the MIM capacitors [2]–[7], the challenge has been to achieve large capacitance density at RF with acceptable leakage current, voltage linearity and reliability under the thermal budget of back-end line process. HfO_2–Al_2O_3 laminate has been reported in metal–insulator-poly-Si (MIS) capacitor for dynamic random access memory application, where low-frequency behavior of capacitance and leakage current are described particularly, showing excellent leakage characteristics and good device reliability [8]. Thus, it is desirable to employ the HfO_2–Al_2O_3 laminate in the MIM capacitor for Si RF and analog MIM capacitor applications. In this work, we use the laminate composition of HfO_2 (5 nm):Al_2O_3 (1 nm) with 1 nm Al_2O_3 as the starting and end layers, respectively. The use of 1 nm Al_2O_3 as the contacting layer to the top and bottom electrodes is intended to improve the meta/dielectric interface quality. As a result, high-performance MIM capacitors using atomic layer deposition (ALD) HfO_2–Al_2O_3 laminates have been demonstrated successfully, suggesting it to be a very promising candidate for next generation RF and mixed signal integrated circuit (IC) applications.

II. EXPERIMENTS

The HfO_2–Al_2O_3 laminate MIM capacitors were fabricated on ~ 4 μm deposited on SiO_2 substrate. The bottom electrode of Ta/TaN was prepared by sputtering, where TaN is employed as a barrier layer and Ta is used to reduce the parasitic resistance from the electrode. The laminate containing alternate Al_2O_3 (1 nm) and HfO_2 (5 nm) layers was deposited using ALD at 320 °C, and the beginning and end layers were 1 nm Al_2O_3. Here, Al_2O_3 was deposited using tri-methyl aluminum and water, while HfO_2 was deposited using $HfCl_4$ and water. Two thicknesses of laminate dielectrics (i.e., 13- and 43 nm) were deposited. Subsequently, TaN was sputtered reactively as the top electrode, followed by annealing at 420 °C in forming gas for 30 min to reduce leakage current. Finally, a photolithography step and dry etching were adopted to define the MIM capacitors. In consideration of RF characterization, the coplanar transmission lines were fabricated, which also served as the top and bottom electrodes; and Al was employed as the contact pads after TaN top electrode formation. The maximum temperature of 420 °C in the device fabrication is compatible with the back-end line integration.

The leakage current was measured using an HP4155B semiconductor parameter analyzer, and the capacitance was measured using an HP4284A precision LCR meter with frequencies varying from 10 kHz to 1 MHz. For RF characterization, the scattering (S) parameters were measured on wafer using

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Manuscript received September 18, 2003; revised October 13, 2003. This work was supported by Institute of Microelectronics, Singapore, under Grant R-263-000-233-490 and the National University of Singapore under Grant R-263-000-221-112. The review of this letter was arranged by Editor S. Kawamura.

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Digital Object Identifier 10.1109/LED.2003.820664

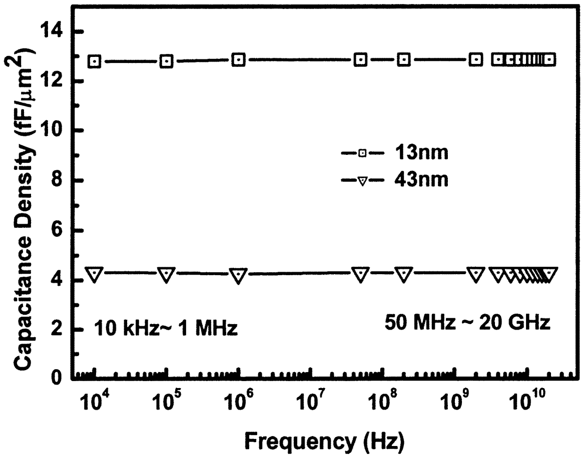


Fig. 1. Dependence of capacitance density on the frequency for 13- and 43-nm laminate MIM capacitors at zero bias.

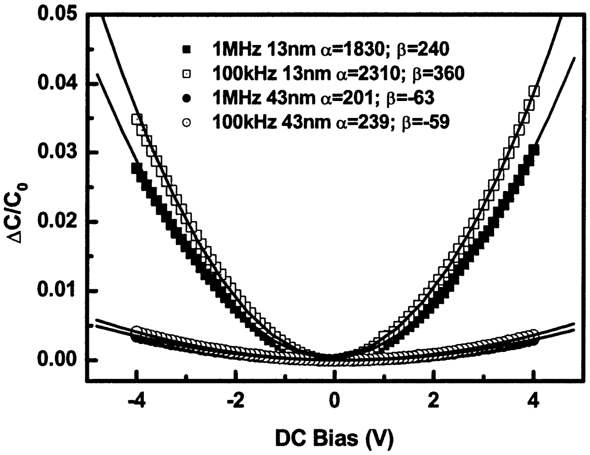


Fig. 2. DC bias dependence of normalized capacitance $(\Delta C/C_0)$ at 100 k and 1 MHz for 13- and 43-nm laminate MIM capacitors.

an HP 8510C network analyzer with the GGBs air coplanar probes (ACP) for ground-signal-ground (GSG) configuration. The measured S-parameters were de-embedded from a dummy device and the high-frequency capacitance plus parasitic parameters were extracted using an equivalent circuit model and IC cap software [9].

III. RESULTS AND DISCUSSION

Fig. 1 shows frequency dependences of capacitance densities for the 13- and 43–nm laminate MIM capacitors. It can be found that the capacitance densities are almost unchanged from 10 k to 20 GHz, indicating excellent dielectric characteristics with frequency. Compared to $AlTiO_x$ MIM capacitor [7], the laminate MIM capacitor exhibits a significant improvement in preservation of capacitance density up to 20 GHz. As evidenced from Fig. 1, the capacitance densities for the 13- and 43-nm laminate MIM capacitors are 12.8 and 4.3 $\text{fF}/\mu\text{m}^2$, respectively. The calculated dielectric constant is ~19, which is close to that of HfO_2 film. Such a high capacitance density of 12.8 $\text{fF}/\mu\text{m}^2$ can easily satisfy the RF bypass capacitor requirement till year 2007 according to the International Technology Roadmap for Semiconductors (ITRS) [10].

Voltage coefficients of capacitance (VCCs) are very important parameters for MIM capacitor applications, and can be obtained by using a second order polynomial equation of $C(V) = C_o(\alpha V^2 + \beta V + 1)$, where C_0 is the zero-biased capacitance, α and β represent the quadratic and linear VCCs respectively. Fig. 2 demonstrates dc bias dependence of normalized capacitance $(\Delta C/C_0)$. The resultant α and β values for different applied frequencies and laminate thicknesses are also presented in Fig. 2, where it is noticed that the VCCs decrease with increasing the laminate thickness and the measurement frequency. As for the 13-nm laminate MIM capacitor with a capacitance density of 12.8 $\text{fF}/\mu\text{m}^2$, the β value is 240 ppm/V at 1 MHz, which is sufficiently low in comparison with the required value (1000 ppm/V) for RF bypass MIM capacitor application [10]. In addition, the temperature dependent capacitance for the laminate MIM capacitors is also measured at 100 kHz from 25 to 125°C, the derived temperature coefficients of capacitance are 182 and 199 ppm/°C for the 13- and 43-nm laminate MIM capacitors, respectively.

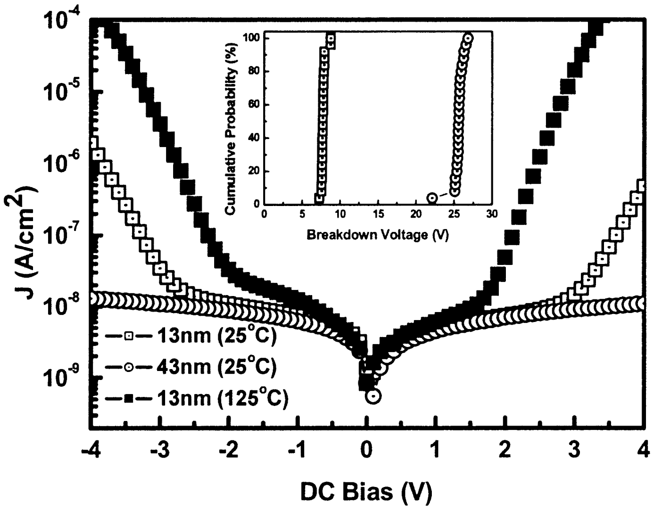
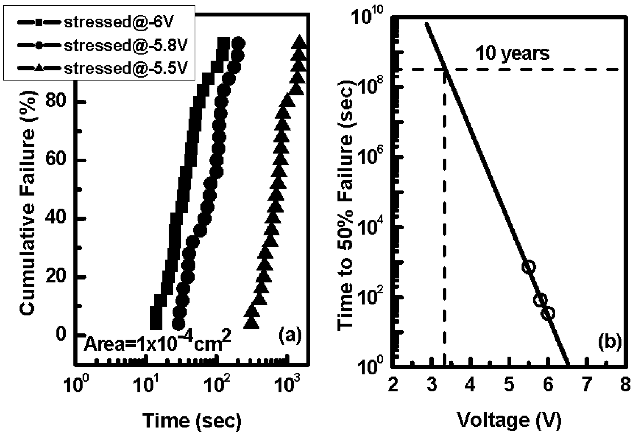


Fig. 3. Leakage current versus dc bias for the 13- and 43-nm laminate MIM capacitors. The insert illustrates the cumulative probability dependent on breakdown voltage of the MIM capacitors with two thicknesses of laminate.

Fig. 3 presents the typical J–V characteristics of the 13- and 43-nm laminate MIM capacitors. Regarding our interested 13-nm laminate MIM capacitor, the leakage current is 3.2×10^{-8} A/cm^2 at 3.3 V in the case of room temperature, and reaches 7.5×10^{-5} A/cm^2 at 3.3 V at the measurement temperature of 125°C, which is markedly superior to ALD HfO_2 and PVD Tb-doped HfO_2 MIM capacitors [3], [4]. On the other hand, the leakage current can be reduced further by optimization of the laminate composition, as suggested by Kukli *et al.* [12]. In addition, the inset in Fig. 3 shows that the breakdown voltage distributions of the laminate capacitors are narrow and consistent. With regard to the 13- and 43-nm laminate MIM capacitors, the corresponding breakdown voltages at 25°C are around 7.7 and 25.6 V ($\sim$6.0 MV/cm), respectively. Such low leakage currents and high breakdown voltages are most likely attributed to the incorporations of thin amorphous Al_2O_3 layers, which exploit the merits of large band gap of Al_2O_3 thereby reducing the leakage and slow oxygen diffusion



(a) (b)

Fig. 4. (a) Cumulative TDDB curves under various constant voltage stressing for 13-nm laminate MIM capacitor measured at room temperature (b) Lifetime projection of 13-nm laminate MIM capacitor, using 50% failure time as the criteria from (a).

TABLE I

COMPARISON OF VARIOUS HIGH CAPACITANCE DENSITY MIM CAPACITORS USING HIGH-κ DIELECTRICS (YEAR 2002–2003)

Reference	[2]	[3]	[4]	[6]	This work
Dielectric	Ta_2O_5 (CVD)	Tb-doped HfO_2 (PVD)	HfO_2 (ALD)	Ta_2O_5 (PVD)	HfO_2-Al_2O_3 laminate (ALD)
Capacitance density (fF/μm^2)	9	13.3	13	9.2	12.8
Leakage (A/cm^2)	—	1×10^{-7}@2V	5.7×10^{-7}@2V	2×10^{-8}@1.5V	7.45×10^{-9}@2V
β (ppm/V)	2050	332	607	2060	240
α (ppm/V^2)	475	2667	853	3580	1830
TCC (ppm/°C)	—	123	—	~200	182

through Al-O matrix improving the interface properties [11]. At the same time, the intermediate amorphous Al_2O_3 layers terminate the continuous crystal growth of HfO_2, thereby eliminate the grain boundary channels extending from one electrode to the other, which is responsible for the reduced conductivity [12]. Additionally, using ALD technique can achieve stoichiometric dielectric films [13], likely enhancing dielectric performance compared to reactively sputtered dielectrics.

The lifetime of the 13-nm laminate MIM capacitor has also been accessed using 1×10^{-4} cm^2 size devices at room temperature. Time to breakdown characteristics of the 13-nm laminate MIM capacitors were evaluated under different constant voltage stress, as shown in Fig. 4(a). The projection of the operating voltage for a 10-year lifetime is 3.3 V by taking the T_{50} as the failure criterion, as illustrated in Fig. 4(b). It indicates that the HfO_2–Al_2O_3 laminate MIM capacitors are of promising reliability, even though obtained at room temperature, for practical applications. Finally, Table I compares our results on HfO_2–Al_2O_3 laminate MIM capacitors with other high capacitance density MIM capacitors reported recently [2]–[4], [6], it is shown that the laminate MIM capacitors exhibit nearly the best electrical performance as well as promising device reliability, suggesting it as a good candidate for next generation MIM capacitor application.

IV. CONCLUSION

High-performance ALD HfO_2–Al_2O_3 laminate MIM capacitors have been demonstrated for the first time. Compared with various high-κ MIM capacitors, our data shows that the laminate MIM capacitor exhibits superior electrical characteristics such as high capacitance density at RF regime, low leakage current and linear VCC, high breakdown field plus promising device reliability. All these indicate that the HfO_2–Al_2O_3 laminate is a very promising dielectric for MIM capacitors in Si analog and RF IC applications.

REFERENCES

[1] T. Remmel, R. Ramprasad, and J. Walls, "Leakage behavior and reliability assessment of tantalum oxide dielectric MIM capacitors," in *Proc. Int. Rel. Phys. Symp.*, 2003, pp. 277–281.

[2] Y. L. Tu, H. L. Lin, L. L. Chao, D. Wu, C. S. Tsai, C. Wang, C. F. Huang, C. H. Lin, and J. Sun, "Characterization and comparison of high-κ metal-insulator-metal (MiM) capacitors in 0.13- μm Cu BEOL for mixed-mode and RF applications," in *Symp. VLSI Tech. Dig.* , 2003, pp. 79–80.

[3] S. J. Kim, B. J. Cho, M. F. Li, C. Zhu, A. Chin, and D.-L. Kwong, "$\mathrm{HfO_2}$ and lanthanide-doped $\mathrm{HfO_2}$ MIM capacitors for RF/mixed IC applications," in *VLSI Tech. Dig.*, 2003, pp. 77–78.

[4] X. Yu, C. Zhu, H. Hu, A. Chin, M. F. Li, B. J. Cho, D.-L. Kwong, P. D. Foo, and M. B. Yu, "A high-density MIM capacitor (13- $\mathrm{fF}/\mu\mathrm{m}^2$) using ALD $\mathrm{HfO_2}$ dielectrics," *IEEE Electron Device Lett.*, vol. 24, pp. 63–65, Feb. 2003.

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

[6] T. Ishikawa, D. Kodama, Y. Matsui, M. Hiratani, T. Furusawa, and D. Hisamoto, "High-capacitance Cu/Ta_2O_5/Cu MIM structure for SoC applications featuring a single-mask add-on process," in *IEDM Tech. Dig.*, 2002, pp. 940–942.

[7] S. B. Chen, C. H. Lai, A. Chin, J. C. Hsieh, and J. Liu, "High-density MIM capacitors using Al_2O_3 and AlTiO_x dielectrics," *IEEE Electron Device Lett.*, vol. 23, pp. 185–187, Apr. 2002.

[8] J.-H. Lee, J. P. Kim, Y.-S. Kim, H.-S. Jung, N.-I. Lee, H.-K. Kang, K.-P. Suh, M.-M. Jeong, K.-T. Hyun, H.-S. Baik, Y. S. Chung, X. Liu, S. Ramanathan, T. Seidel, J. Winkler, A. Londergan, H. Y. Kim, J. M. Ha, and N. K. Lee, "Mass producion worthy $\mathrm{HfO_2}$–$\mathrm{Al_2O_3}$ laminate capacitor technology using Hf liquid precursor for sub-100 nm DRAMs," in *IEDM Tech. Dig.*, 2002, pp. 221–224.

[9] *IC-CAP Manual*, Hewlett Packard, 1998.

[10] *The International Technology Roadmap for Semiconductors (ITRS) 2001*.

[11] G. D. Wilk, R. M. Wallace, and J. M. Anthony, "High-κ gate dielectrics: Current status and materials properties considerations," *J. Appl. Phys.*, vol. 89, pp. 5243–5275, Oct. 2001.

[12] K. Kukli, J. Ihanus, M. Ritala, and M. Leskela, "Tailoring the dielectric properties of HfO_2–Ta_2O_3 nanolaminates," *Appl. Phys. Lett.*, vol. 68, no. 26, pp. 3737–3739, 1996.

[13] D. Hausmann, J. Becker, S. Wang, and R. G. Gordon, "Rapid vapor deposition of highly conformal silica nanolaminates," *Science*, vol. 298, pp. 402–406, Oct. 2002.