High-Density MIM Capacitors Using Al_2O_3 and $AlTiO_x$ Dielectrics

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

***Abstract*—We have investigated the electrical characteristics of Al_2O_3 and $AlTiO_x$ MIM capacitors from IF (100 KHz) to RF (20 GHz) frequency range. Record high capacitance density of 0.5 and 1.0 μF/cm^2 are obtained for Al_2O_3 and $AlTiO_x$ MIM capacitors, respectively, and the fabrication process is compatible to existing VLSI backend integration. However, the $AlTiO_x$ MIM capacitor has very large capacitance reduction as increasing frequencies. In contrast, good device integrity has been obtained for Al_2O_3 MIM capacitor as evidenced from the small frequency dependence, low leakage current, good reliability, small temperature coefficient, and low loss tangent.**

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

I. INTRODUCTION

THE MIM capacitor is one of the essential devices for analog and RF ICs, but the area of total MIM capacitors usually occupies a large portion of the whole ICs. To increase the circuit density and reduce the cost, large capacitance density is highly desirable. However, the attempt to increase the capacitance density $\varepsilon_0 k/t_d$ by reducing the dielectric thickness (t_d) usually generates undesired high leakage current and poor RF loss tangent. The only choice left is to use high-k dielectrics [1]–[5], and good IF to RF performance is obtained in high-k $AlTiO_x$ and Al_2O_3 MOS capacitors [5]. In this paper, we have further investigated the device integrity of high-k $AlTiO_x$ and Al_2O_3 MIM capacitors. In comparing with the MOS capacitors, the MIM capacitors faces the different challenge of low process temperature ($\leqq$400 °C) for VLSI back-end process integration [6]. Under this process constraint, we have achieved record high capacitance density of 0.5 and 1.0 μF/cm^2 using respective Al_2O_3 and $AlTiO_x$ MIM capacitors, but the $AlTiO_x$ MIM capacitor has fast capacitance reduction as frequency increases. In contrast, the Al_2O_3 MIM capacitor has good device integrity of weak frequency and temperature dependence, small leakage current, and low-loss tangent that is good for circuit application.

II. EXPERIMENTAL

The MIM capacitors were fabricated on 5000 Å SiO_2 deposited 4-in Si substrate. In consideration of RF characterization, high-k Al_2O_3 and $AlTiO_x$ dielectrics with coplanar transmission lines [7]–[10] were fabricated on SiO_2, where the transmission line also serves as top and bottom electrodes of MIM capacitor. Then thin Al or Ti/Al bi-layer was deposited under high vacuum condition on patterned bottom Pt/Ti transmission line, followed by subsequent oxidation and annealing at 400 °C to form respective high-k Al_2O_3 and $AlTiO_x$ [3]–[5]. The motivation of utilizing $AlTiO_x$ is to increase k and capacitance density. In addition, it also preserves the merit of slow oxygen diffusion through Al–O matrix. Finally, Al is used for both top capacitor electrode and transmission line, and the device area is 50 μm × 50 μm. The Al_2O_3 and $AlTiO_x$ capacitors were measured using an HP4284A precision LCR meter at 100 KHz and 1 MHz, while the S-parameters were measured by HP8510C network analyzer ranging from 200 MHz to 20 GHz. The measured S-parameters are de-embedded from a dummy device and the high-frequency capacitance plus resistance values are extracted using an equivalent circuit model.

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S. B. Chen, C. H. Lai, and A. Chin are with the Department of Electronics Engineering, National Chiao Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: u8711543@cc.nctu.edu.tw; achin@cc.nctu.edu.tw).

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

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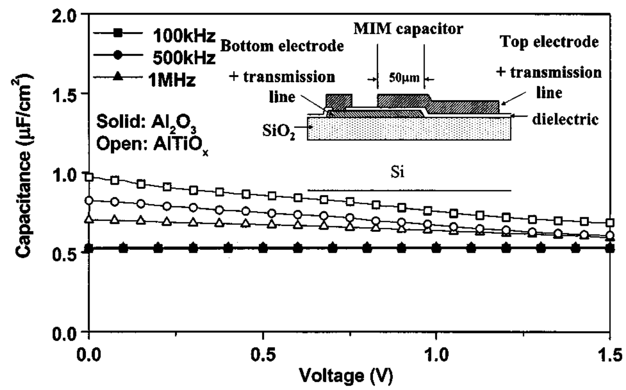

Fig. 1. Capacitance–voltage (C–V) characteristics of (a) Al_2O_3 and (b) $AlTiO_x$ MIM capacitors at the frequencies of 100 kHz, 500 kHz, and 1 MHz. The measured area is 50 μm × 50 μm.

III. RESULTS AND DISCUSSION

We have first measured the low-frequency capacitance. Fig. 1 depicts the C–V characteristics for Al_2O_3 and $AlTiO_x$ at frequencies ranging from 100 KHz to 1 MHz, respectively, while the inserted figure is the cross-sectional view of device including the MIM capacitor and transmission line. Record high-capacitance density of 0.5 and 1.0 μF/cm^2 are measured for respective Al_2O_3 and $AlTiO_x$ at 100 KHz, but $AlTiO_x$ capacitor shows fast capacitance reduction and large voltage dependence at this IF region. Therefore, the merit of high-capacitance density for $AlTiO_x$ capacitor is vanished even increasing frequency to 1 MHz. In contrast, the Al_2O_3 MIM capacitor shows much less capacitance change at this

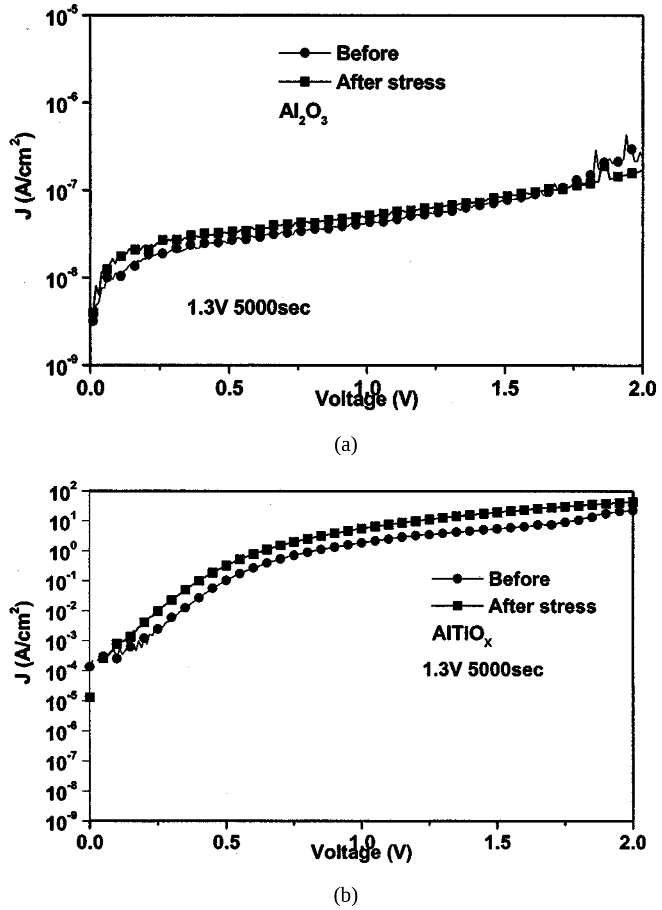

Fig. 2. J–V characteristics of (a) Al_2O_3 and (b) $AlTiO_x$ MIM capacitors before and after stress. The small change of leakage current in Al_2O_3 MIM capacitor after stress suggests the excellent reliability.

frequency range. The average voltage dependence of Al_2O_3 MIM capacitor from 100 KHz to 1 MHz follows the voltage dependence of $C_o(\alpha \times V^2 + \beta \times V + 1)$, where C_o, β, and α are 0.5263 μF/cm^2, 1888 ppm/V, and 2051 ppm/V^2, respectively. Although the first and second-order voltage coefficients are larger than SiO_2 and Si_3N_4 [11] and may be due to the thinner thickness used here, the capacitance change is only ~2% for a 3.3 V applied voltage that is acceptable for most circuit applications.

Fig. 2(a) and (b) shows the J–V characteristics of Al_2O_3 and $AlTiO_x$ MIM capacitors before and after constant voltage stress, respectively. The leakage current in Al_2O_3 capacitor is 4.3×10^{-8} A/cm^2 at 1 V, which is several orders of magnitude smaller than that in $AlTiO_x$ capacitor at the same physical thickness of 120 Å. The large leakage current in $AlTiO_x$ capacitor may be due to both smaller bandgap and weaker Ti–O bond related higher defects, which is further confirmed by the large stress-induced leakage current (SILC) in $AlTiO_x$ MIM capacitor. In contrast, only small amount of SILC is observed for Al_2O_3 capacitor that demonstrates the good reliability for circuit application.

Fig. 3 illustrates the temperature dependence for Al_2O_3 and $AlTiO_x$ MIM capacitors. Low temperature coefficient of capacitance (TCC) of 109, 138 and 208 PPM/°C are measured in Al_2O_3 MIM capacitor at 150 °C and respective 1 MHz,

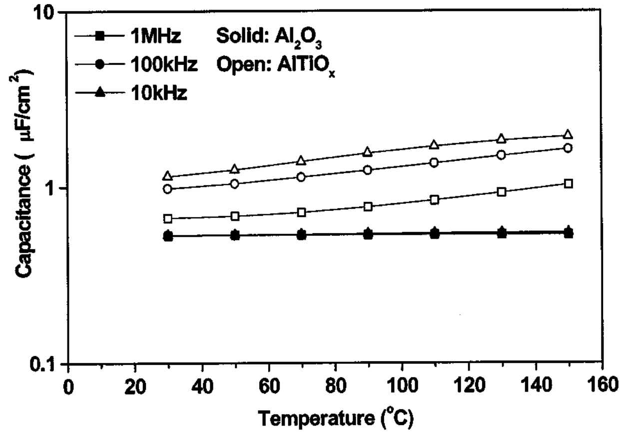

Fig. 3. Frequency and temperature dependence of capacitance for Al_2O_3 and $AlTiO_x$ MIM capacitors.

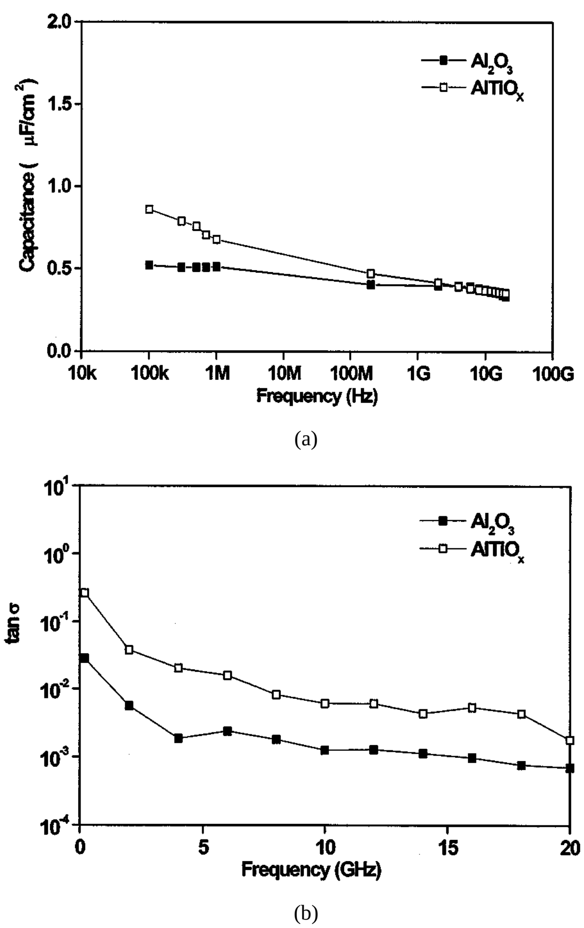

Fig. 4. (a) Frequency-dependent capacitance and (b) loss tangent for Al_2O_3 and $AlTiO_x$ MIM capacitors.

100 KHz, and 10 KHz, which is comparable with the temperature coefficient of Si_3N_4 capacitor reported in the literature [11]. In contrast, near one order of magnitude larger TCC is found in $AlTiO_x$ capacitors that make this capacitor have only limited application.

Fig. 4(a) and (b) demonstrate the frequency-dependent capacitance reduction and the loss tangent for various gate dielectrics, respectively. Only a small amount of capacitance reduction for Al_2O_3 MIM capacitor is found over the entire frequency range from 100 KHz to 20 GHz. In sharp contrast, large capacitance reduction is observed for $AlTiO_x$ MIM capacitor, and the capacitance gradually reduces to the same value as Al_2O_3 MIM capacitor. The reason why $AlTiO_x$ MIM capacitor exhibits severe capacitance reduction may be due to the high defect density and slow time constant of traps from Ti–O_x. The high RF performance of Al_2O_3 MIM capacitor can also be evidenced from the very low loss tangent even at a large capacitor area of 2500 μm^2, which is one order of magnitude smaller than that of $AlTiO_x$ capacitor. However, those values of loss tangent are still low enough to be used for RF application [12].

IV. Conclusion

Higher k dielectric is not necessary to give higher capacitance at high frequencies and other device integrity should be considered. The Al_2O_3 MIM capacitor exhibits low leakage current, small frequency-dependent capacitance reduction, low TCC, low loss tangent, and good reliability that is suitable for circuit application at high frequencies.

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