Very High-Density (23 fF/μm^2) RF MIM Capacitors Using high-κ TaTiO as the Dielectric

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***Abstract*—A very high density of 23 fF/μm^2 has been measured in RF metal–insulator–metal (MIM) capacitors which use high-κ TaTiO as the dielectric. In addition, the devices show a small reduction of 1.8% in the capacitance, from 100 kHz to 10 GHz. Together with these characteristics the MIM capacitors show low leakage currents and a small voltage-dependence of capacitance at 1 GHz. These TaTiO MIM capacitors should be useful for precision RF circuits.**

***Index Terms*—Capacitor, RF metal–insulator–metal (MIM), TaTiO.**

I. INTRODUCTION

According to International Technology Roadmap for Semiconductors (ITRS), continuous down-scaling of the size of metal–insulator–metal (MIM) capacitors is required to reduce chip size and the cost of analog and RF ICs [1]. The use of a high--κ dielectric [2]–[15] is the only way to achieve this goal, since decreasing the dielectric thickness (t_d) to achieve high capacitance density $(\varepsilon_0\kappa/t_d)$ degrades the leakage current, loss tangent and voltage-dependence of the capacitance $(\Delta C/C)$. Hence, the high-κ dielectric in MIM capacitors has evolved from using SiON $(\kappa \sim 4-7)$ [3]–[5] and Al_2O_3 $(\kappa = 10)$ [13] to HfO_2 $(\kappa \sim 22)$ [7]–[11] or Ta_2O_5 $(\kappa \sim 25)$ [12], [14]. To increase the κ value beyond 25, the dielectric TiO_2 is a potential candidate, since it can display very high-κ (~80). However, the large leakage current from crystallization of the TiO_2 is a major limitation for device applications. Here, we report the use of TiTaO as the dielectric, and show capacitors with low leakage current and without crystallization, even after backend processing. We report devices with a high density of 23 fF/μm^2, a high-κ value of 39–45 (beyond the previous $\kappa \sim 25$ barrier), and low leakage current of 1.2×10^{-6} A/cm^2. This performance of the TiTaO MIM capacitors is accompanied by a small $\Delta C/C$ of 550 ppm at 1 GHz. Compared with current technology these high performance capacitors can drastically reduce the RF capacitor area [1], yet can be fabricated with full compatibility with current VLSI process lines.

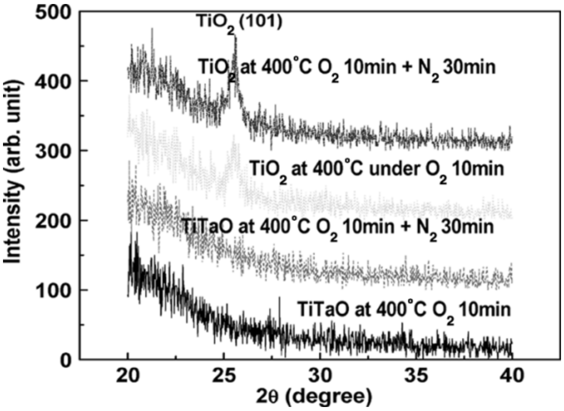

Fig. 1. XRD patterns of TiO_2 and TiTaO dielectric layers, ~28 nm thick, after 400 °C O_2 oxidation and N_2 annealing.

II. EXPERIMENTAL PROCEDURE

High-κ TiTaO MIM capacitors were fabricated on 4-in Si wafers. First, a 2-μm-thick isolation SiO_2 was deposited on the Si substrates. The bottom capacitor electrodes were formed by depositing 0.05-μm TaN on a 1-μm Ta layer, followed by patterning. Then, a 17-nm-thick $Ti_xTa_{1-x}O$ $(x \sim 0.6)$ was deposited on the TaN/Ta electrode, followed by 400 °C oxidation and annealing. Finally, Al was deposited and patterned to form the top capacitor electrode and RF transmission lines. For comparison purposes devices with TiO_2 as the dielectric was also fabricated using the same process. The fabricated RF MIM capacitors were characterized using an HP4284A precision LCR meter from 10 KHz to 1 MHz, and an HP8510C network analyzer for the S-parameter measurements from 200 MHz to 20 GHz [13]–[15]. The series inductance and RF pads were deembedded from a "through" and "open" transmission lines [16], [17], respectively. The RF frequency capacitance was extracted from the measured *S*-parameters using an equivalent circuit model [15].

III. RESULTS AND DISCUSSION

Fig. 1 shows the X-Ray diffraction (XRD) patterns of 28-nm-thick TiO_2 and TiTaO layers, which were used to examine the

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Manuscript received May 25, 2005; revised July 19, 2005. This work was supported in part by the National Science Council of Taiwan, R.O.C. under Grant 92-2215-E-009-031. The review of this letter was arranged by Editor C.-P. Chang.

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Digital Object Identifier 10.1109/LED.2005.856708

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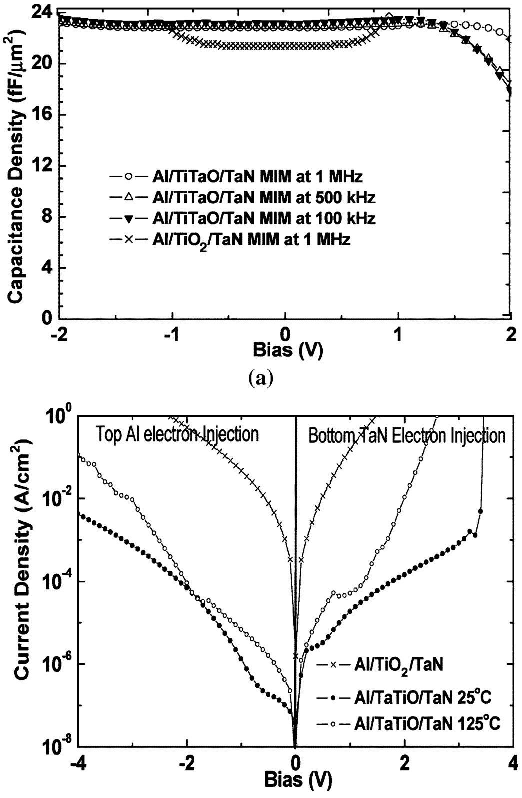


(a)

(b)

Fig. 2. (a) *C–V* and (b) *J–V* characteristics of TiO_2 and TaTiO capacitors. The leakage current is lower in the TiTaO capacitors. The leakage currents at both 25 °C and 125 °C from top and bottom electrodes are shown for comparison. The capacitor size is 20×20 μm^2.

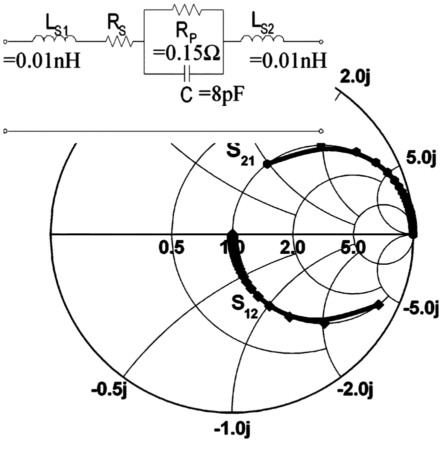
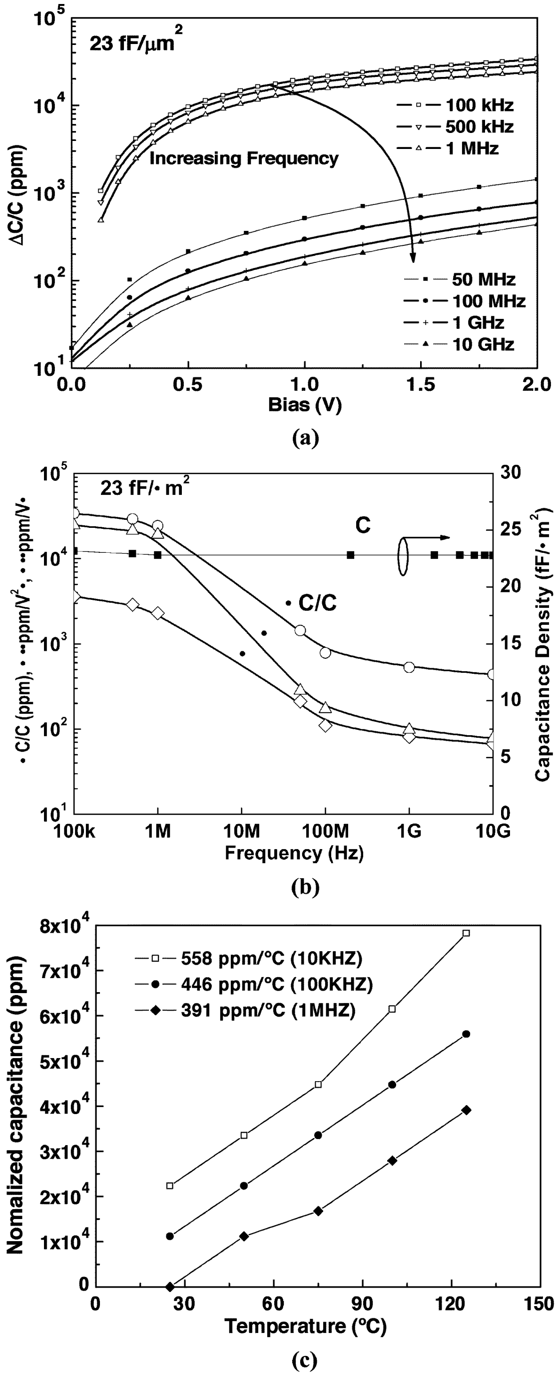


Fig. 3. Scattering parameters of a TiTaO MIM capacitor, from 200 MHZ to 20 GHz, after deembedding the through transmission line. Insert: the equivalent circuit model used for capacitance extraction. The capacitor size is 20×20 μm^2.

thermal stability on their amorphous structure. Significant crystallization of the TiO_2 was measured after a 400 °C O_2 treatment for 10 min which became worse after subsequent 30 min N_2 annealing. In contrast the TiTaO was amorphous after the same thermal cycle. This good stability after backend thermal treatment is important in reducing the leakage current in RF MIM capacitors. Further trading off the Ti composition <0.6 in Ti_x $Ta_{1-x}O$ with thermal stability is necessary if higher thermal cycle is used such as 450 °C and above.



(a)

(b)

(c)

Fig. 4. (a) $\Delta C/C$–V characteristics of a TiTaO MIM capacitor. The data for frequencies >1 MHz were obtained from the *S*-parameters. (b) Frequency dependent capacitance density, $\Delta C/C$, α and β for a TiTaO MIM capacitor biased at 2 V. (c) Temperature-dependence of capacitance (TCC). The capacitor size is 20×20 μm^2.

Fig. 2(a) and (b) shows the *C–V* and *J–V* characteristics of TaTiO and TiO_2 MIM capacitors. For the TiTaO device a very high capacitance density of 23 fF$/\mu$m^2 was measured, giving a high-κ value of ~39, although more detailed study in a different experiment with Transmission Electron Microscopy for thickness calibration gives a κ value of ~45 [18]. This κ value is greater than the $\kappa \sim 22-25$ value for HfO_2 and Ta_2 O_5 which are used in DRAM. However the TiO_2 MIM capacitor showed an unusual capacitance variation at voltages above ±0.75 V. The poor C–V for the TiO_2 MIM capacitor is thought to be related to its large leakage current, Fig. 2(b), which may be due to the current conduction through grain boundaries of the poly-crystalline TiO_2. In contrast, constant capacitance values, with little voltage and frequency dependence, were found for the TiTaO MIM capacitor. The TiTaO MIM capacitors have ∼5–7 orders of magnitude lower leakage current than that for the TiO_2 devices. Note that although the ITRS only specifies the capacitance density and Q-factor [1], the leakage current was as low as 5 pA $(1.2 \times 10^{-6}$ A/cm$^2)$ at 1 V for a large 9.2 pF capacitor (20 × 20 μm^2 in size) and lower than the leakage current of sub-100 nm transistors [16]. The leakage current, injecting electrons from the Al contact, is lower than that from using the lower TaN electrode. This is due to the better interface for the Al, which also gives better voltage and frequency dispersion in the C–V curves. The leakage current is even worse at 125 °C and the using high work-function metal electrode to reduce the leakage current will be needed [19]–[21].

Fig. 3 shows the measured S-parameters for a TiTaO MIM capacitor, where the capacitance at RF frequencies can be extracted from S-parameters using the equivalent circuit model shown in the insert. Fig. 4(a) displays the $\Delta C/C - \mathrm{V}$ characteristics, where the data >1 MHz were calculated from the measured S-parameters using a circuit-theory derived equation [10]. The frequency dependent capacitance value is shown in Fig. 4(b). The capacitance reduction of 1.8% from 100 kHz to 10 GHz indicates good device performance over the IF to RF range. However, the rapid $\Delta C/C$ reduction with increasing frequency above megahertz regime may be due to the trapped carriers being unable to follow the high frequency signal [10], [15], [17]. Here, the typical carrier lifetime of trap-related Shockley–Read–Hall recombination is in the range ms to μs. The first order voltage linearity (β) and quadratic voltage linearity (α) [7] are also shown in Fig. 4(b). The small $\Delta C/C$ of 550 ppm, low α of 81 $\mathrm{ppm/V^2}$ and β of 98 ppm/V at 1 GHz are important for high-speed analog/RF IC applications [7]–[11]. Fig. 4(c) shows the temperature-dependence of capacitance (TCC). Again, similar reduction of both capacitance and TCC are found with increasing frequency.

IV. CONCLUSION

Very high 23 fF/μm^2 capacitance density, with a capacitance reduction of 1.8% from 100 kHz to 10 GHz, and a small 550 ppm $\Delta C/C$ at 1 GHz were simultaneously achieved in novel high-κ TiTaO MIM capacitors processed at 400 °C. These MIM capacitors should be suitable for precision RF circuits.

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